Direct Photon Production

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Outline

1. Physics Motivations for Prompt Photon Productions
2. Production Mechanisms for Prompt Photons
3. Measurement Techniques for Isolated Photons
4. Experimental Results
   - Part I. Prompt Photon Production at Tevatron
     → Summary of CDF/DØ Run I/II Photon Results and kT issues
   - Part II. Prompt Photon Productions at HERA
     → Summary of ZEUS/H1 Photon Results and kT issues
   - Part III. Prompt Photon Productions at LEPII
     → Summary of LEPII Photon Results
5. Summary and Outlook

Preamble

- Photons have a point-like coupling to the hard interaction, allowing for prompt probes and precision tests of perturbative QCD

- Experimentally, the 4-vector of the photon can be measured more precisely than that of a jet, again pointing to precision tests of pQCD

- In this lecture, I will focus on photon production in hadron-hadron (@ Fermilab), lepton-hadron (@ DESY), lepton-lepton (@ LEPII) collisions
  - The dominance of the gluon-Compton scattering diagram allows the potential for measuring the gluon distribution in the proton (although some theoretical complications are currently making that a bit difficult)

- I will discuss about some puzzles in direct photon production
  - e.g. effective parton kT, NLO resummation etc…

- Important to understand QCD of direct (prompt) photon production in order to reliably search for new physics and Higgs (see next slide)

Prompt Photon Motivation [I]

- As long as 20 years ago, direct(prompt) photon measurements were promoted as a way to:
  - Avoid all the systematics associated with jet ID and measurement
    → photons are simple, well measured EM objects
    → emerge directly from the hard scattering without fragmentation
  - Hoped-for sensitivity to the gluon content of the nucleon
    → "QCD Compton process"
- In the meantime…
  Jet measurements have become much better understood
- Lower photon cross sections and ease of triggering on EM objects lead to photon data being at much lower E_T than typical jet measurements
  - Turn out to be susceptible to QCD effects at the few GeV level
- Photons have not been a simple test of QCD and have not given input to parton distributions, and they continue to challenge our ability to calculate within QCD

Photon Signatures of New Physics

- We can search for new physics with photons in the final state
- Why photon?

Empirically interesting !!

- Radiative decays of new ptl Predicted by SUSY, Technicolor, LED and other EWSB produce High E photons in the final state.
- Anomalous multi-boson coupling lead to hadronic production of photons in association with other gauge boson (WWgg, ZZgg)

High P_T physics with photons and MET

- SUSY (N_2 -> gN_1, light gravitinos)
- Large Extra Dimensions
- Excited leptons
- Technicolour
- New dynamics
- Higgs: V+Higgs -> V+gg
- W/Z+g production

SUSY Models

- Minimal SUSY extension of SM (MSSM)
- Minimal Super-Gravity (mSUGRA)
- Gauge Mediated SUSY Breaking (GMSB)

SM Higgs

$H \to \gamma\gamma$ is a discovery channel at LHC

Published CDF Photon Analyses

Photon + Dijet	Dijet Properties (QCD)	PRD 57 (98)
Photon + Muon	Intrinsic Charm (QCD)	PRL 77 (96), PRD 60 (99)
Photon + jet + X	Jet eta disribution (QCD)	PRD 57 (98)
Photon + X	Cross Section (QCD) Angular distribution(QCD)	PRL 73 (94), PRD 48(93), PRL 68 (92), PRL 71 (93)
Diphoton + X	eeggMet event (Search)	PRL 81 (98), PRD 59 (99)
Diphoton	Cross Section (QCD)	PRL 70 (93)
Diphoton + W/Z	Higgs/sGoldstino(Search)	
Photon + Lepton+X	Signature-based (Search)	
Photon + Z	Anomalous Couplings	PRL 74 (95)
Photon + W	Anomalous Couplings	PRL 74 (95)
Photon + b-jet + X	Techni-Omega (Search)	PRL 83 (99)
Photon + b	SUSY	
Photon + D*	W -> photon + D*	PRD 58 (98)
Photon + track	W -> Photon + pion	PRL 76 (96), PRL 69 (92) PRL 58 (98)

Published D0/ZEUS Photon Analyses

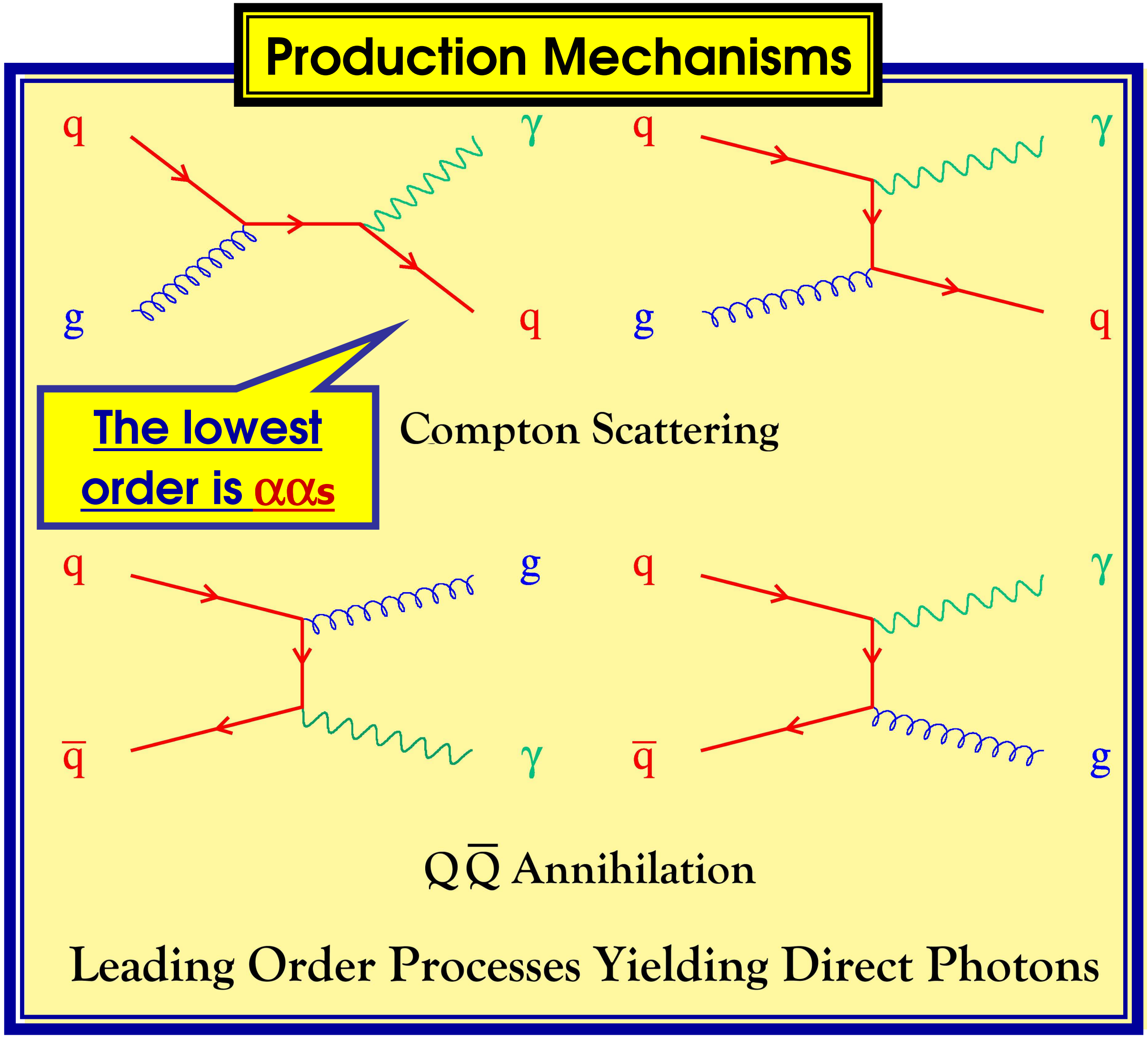
Photon + X	Cross Section (QCD)	PRL 77 (96)
Diphoton + Met	SUSY (Search)	PRL 78 (97), PRL 80 (98)
Diphoton	Dirac Monopoles (Search)	PRL 81 (98)
Diphoton	LED (Search)	PRL 86 (01)
Diphoton + Dijet	Vhiggs (Search)	PRL 82 (99)
Many	Sleuth (Search)	PRL 86 (01), PRD 64 (01)
Z + Photon	Anomalous Couplings	PRL 75 (95), PRD 56 (97)
W + Photon	Anomalous Couplings	PRL 78 (97), PRD 58 (98)
b’	Heavy Quark (Search)	PRL 78 (97)
Photon+Dijet + Met	SUSY (Search)	PRL 82 (99)
Photon + Z0	Anomalous Couplings	PRL 78 (97)

Photon + Jet	First Observation (QCD)	PL B 413 (97)
Inclusive Photon	Cross Section (QCD)	PL B 472 (00)
Photon + Jet	Effective Parton kT(QCD)	PL B 511 (01)
DIS Photon (+Jets)	Cross Section (QCD)	DIS 2002

Why High Energy Photons?

- Photons have a point-like coupling to the hard interaction, allowing for direct probes and precision tests of perturbative QCD
- Experimentally, the 4-vector of the photon can be measured more precisely than that of a jet, again pointing to precision tests of QCD
- As long as 20 years ago, prompt photon measurements were promoted as a way to:
  - avoid all the systematics associated with jet ID and measurement
    - ✓ Photon can be measured more precisely than jet.
    - ✓ emerge directly from the hard scattering without fragmentation
  - allows the potential for measuring the gluon distribution in the proton
- Photons have not been a simple test of QCD and have not given input to parton distributions, and they continue to challenge our ability to calculate within QCD
- In addition, can search for new physics with photons in the final states:
  - Higgs: $H \rightarrow \gamma\gamma$ is a discovery channel at LHC
  - Recent SUSY Models: Supergravity Model (mSUGRA), GMSB Model
  - Technicolor: Photon + dijet signatures, Diphoton resonances
  - Large Extra Dimensions, etc…

Prompt Photon Production at Tevatron (I)



Leading order structure has the photon recoiling against a jet

- **Large PT data test pQCD and help constrain fragmentation functions and PDFs.**
- **The LO processes for prompt photon are relatively simple.**
- **Prompt photon production is sensitive to the g distribution.**
- **The lowest order is $\alpha\alpha_s$: LO structure has the photon recoiling against a jet**
- **Next order(HO) is $\alpha\alpha_s\alpha_s$: photon is balanced by 1 or 2 jets in the final state**

- **Complicated by**

→ parton distributions: a hadron collider is a broad-band quark and gluon collider

→ both the initial and final states can be colored and can radiate gluons

→ underlying event from proton remnants

Prompt Photon Production at the Tevatron

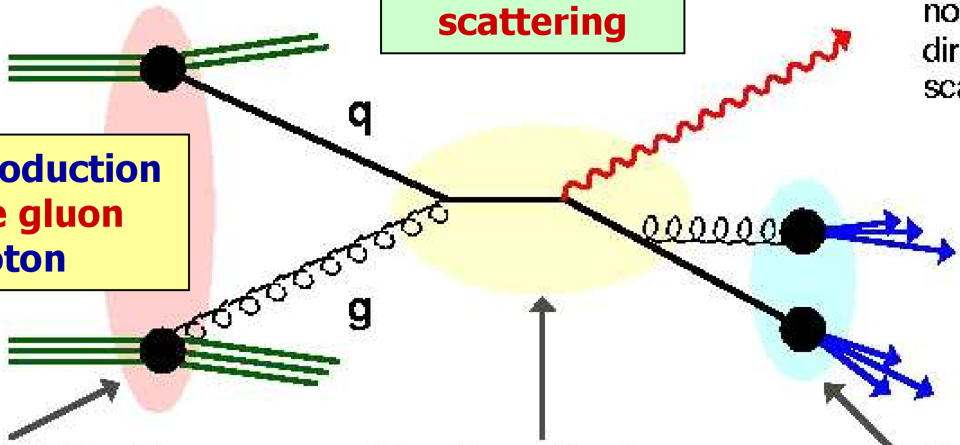
<u>Simplest process</u>

$p\bar{p} \to \gamma + \text{jet}$

QCD Compton scattering

photon
no fragmentation $\to$ direct probe of the hard scattering process

Prompt photon production is sensitive to the gluon distribution in proton



Both the initial and final states can be colored and can radiate gluons

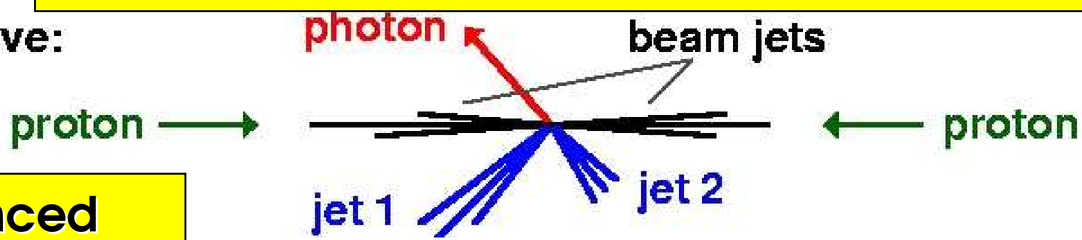
Parton Distributions
Non-perturbative, must be experimentally determined, but are universal

Hard scattering
High momentum transfer
Perturbative QCD

Fragmentation
(quark, gluon) $\to$ jet

Experimentally we find that at about one third of the photon events have a second jet of significant E_T

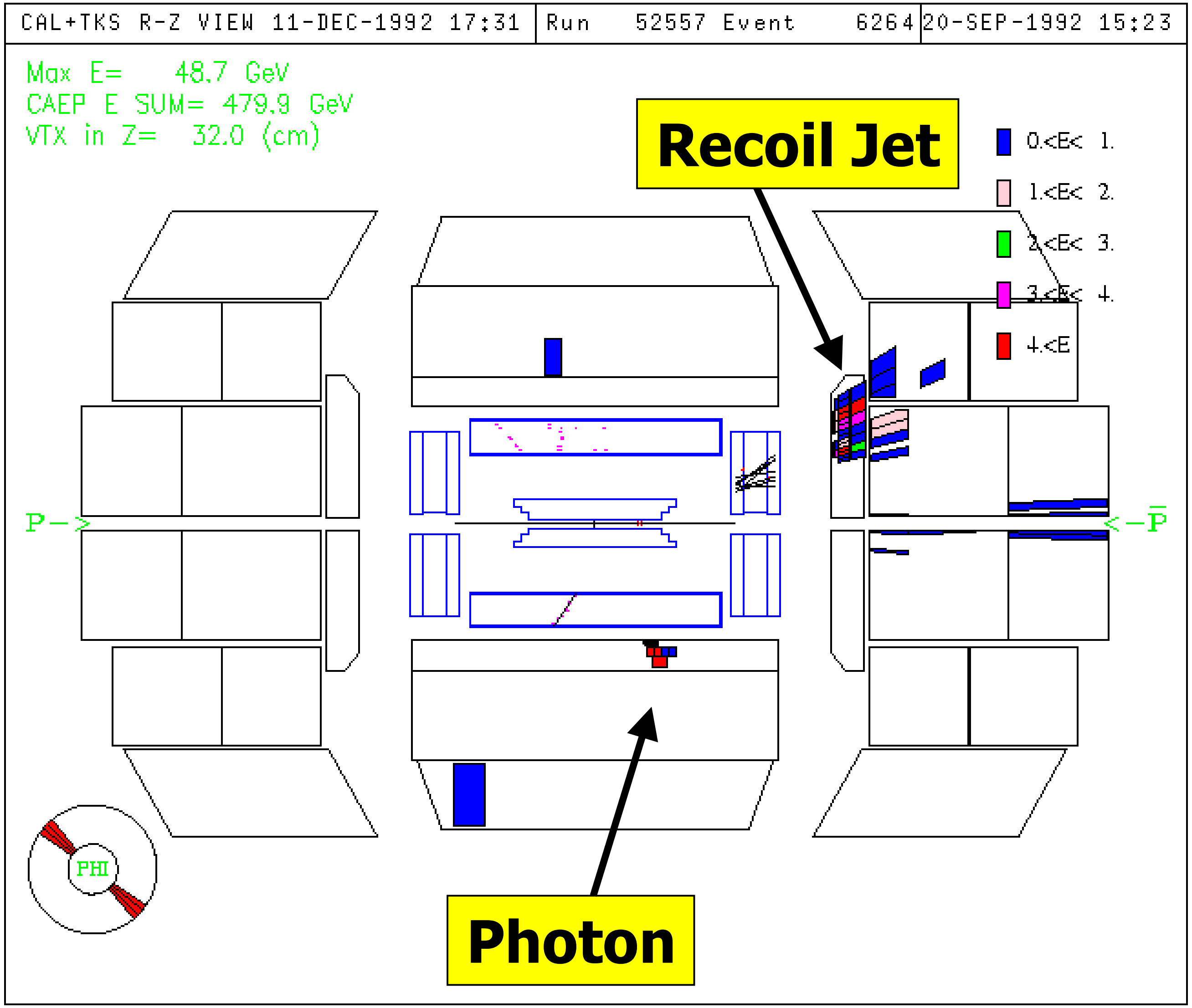
What we observe:



Recoil Jets

Photon is balanced by 1 or 2 jets in final state

Typical Direct Photon Candidate Event



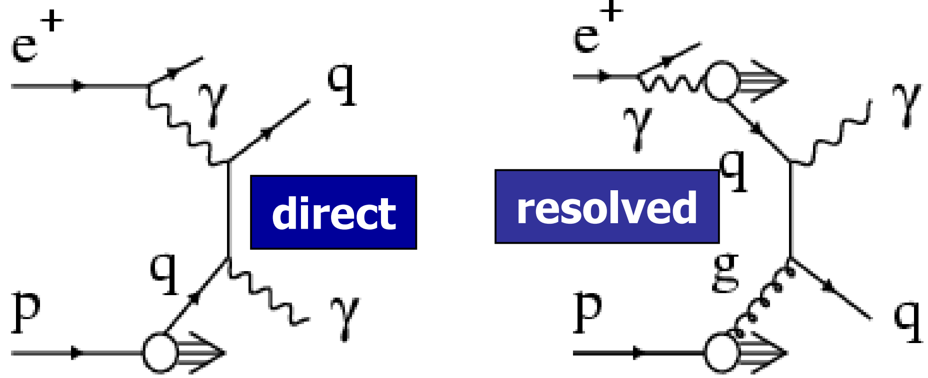
Prompt Photon Production at HERA

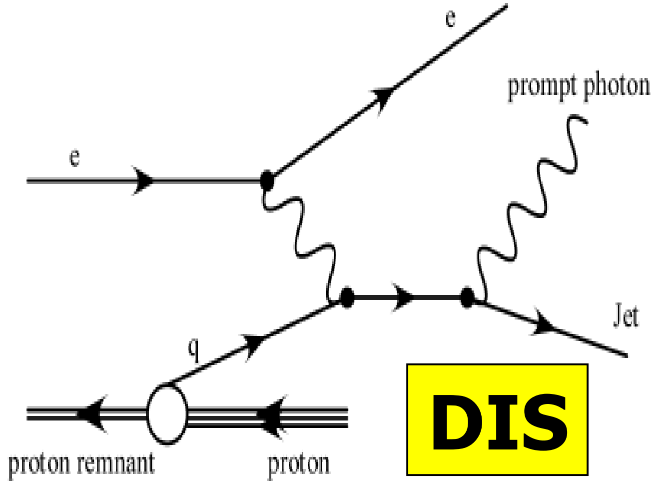
- Prompt photons can be produced in direct and resolved interactions.
- In photoproduction, <u>only one LO direct process: "Direct Compton"</u>
- HERA kinematics favor gluon from proton and quark from incoming photon (see resolved process)

- In DIS, prompt photons emitted by the direct process with no resolved contribution

- Sensitive to quark densities in photon at HERA
- The clean signature of the prompt photon can provide <u>a good means to test QCD; photon structure, intrinsic parton momentum(kT), NLO</u> etc...

Photoproduction



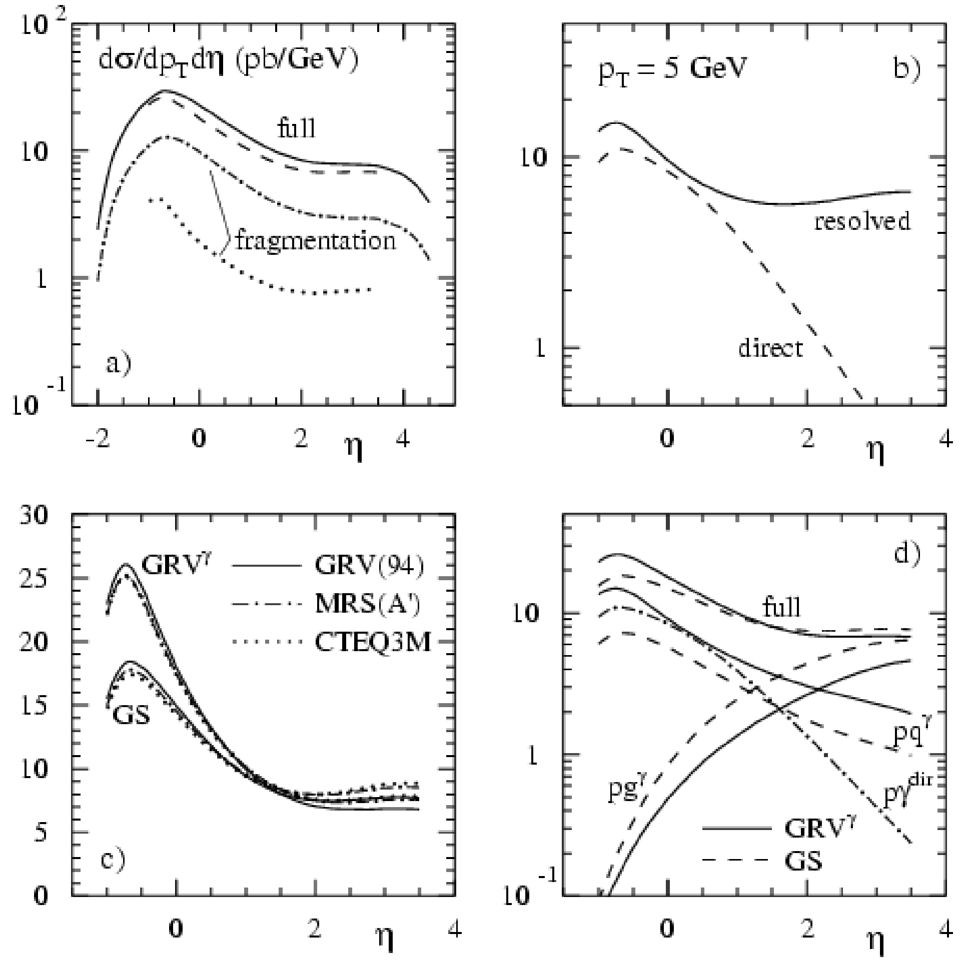


DIS

* prompt photon is produced directly in the hard scattering

Prompt Photon Production at HERA

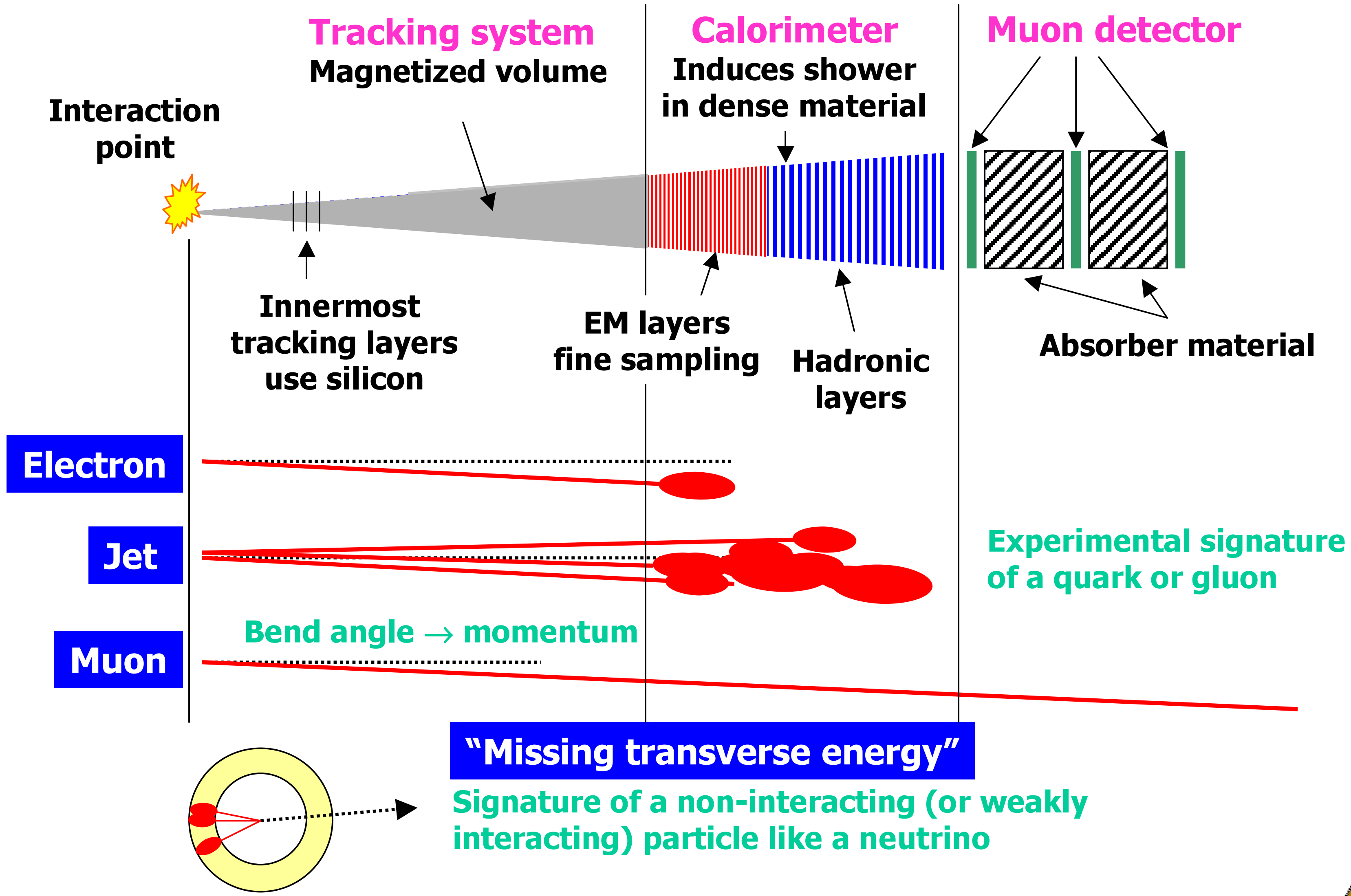
NLO QCD Predictions



NLO QCD…

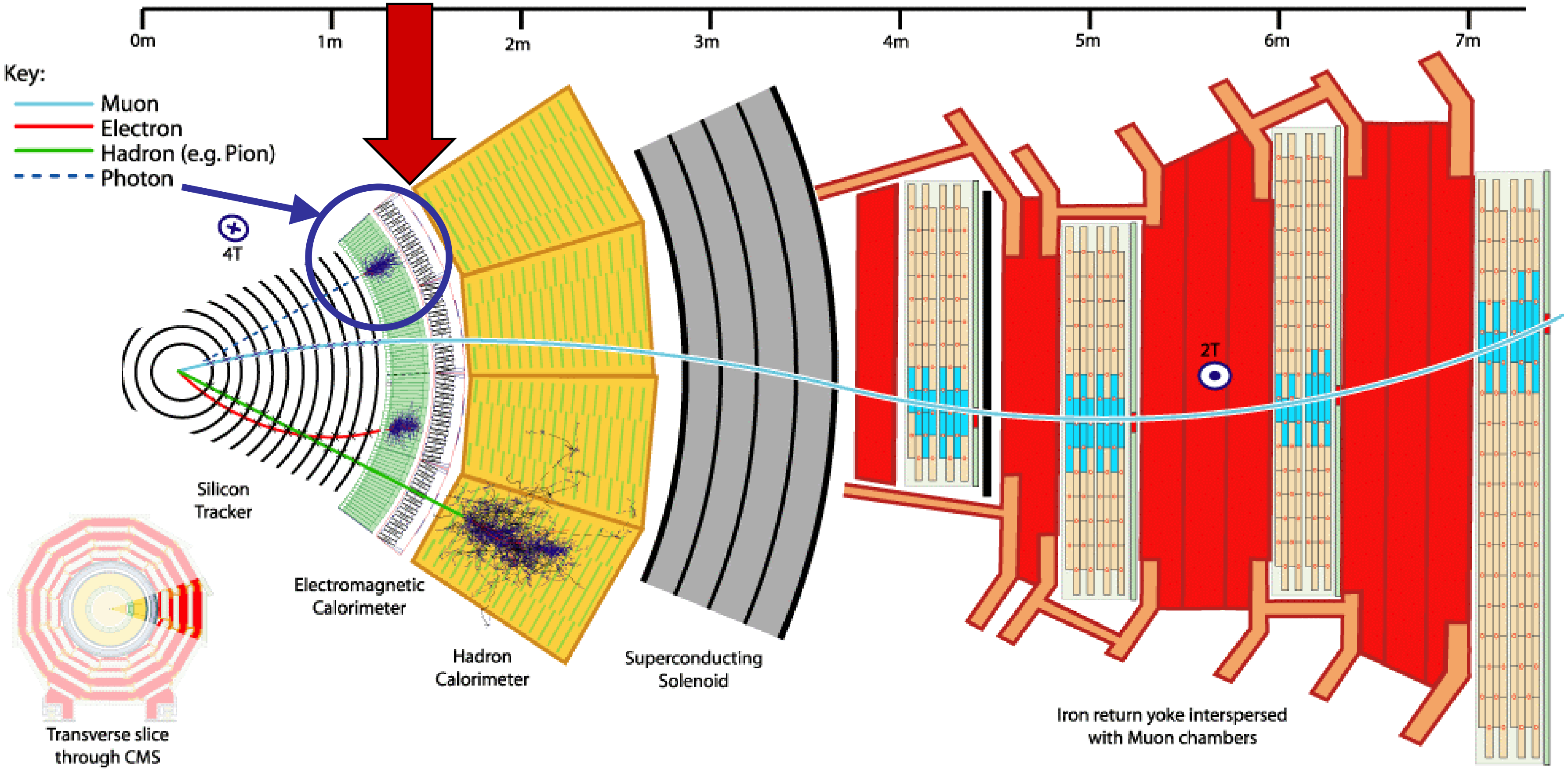
- photon pseudorapidity distribution is sensitive to the photon structure
- Quark
  → backward region
  (eta < 2)
- Gluon
  → forward region (eta > 2)
- NLO QCD Calculation
  → Gordon and Vogelsang

Typical HEP Detector System



For example, CMS detector at LHC

Identification of Photon Signal



Photon candidates: isolated electromagnetic showers in the calorimeter, with no charged tracks pointing at them

Photon Identification

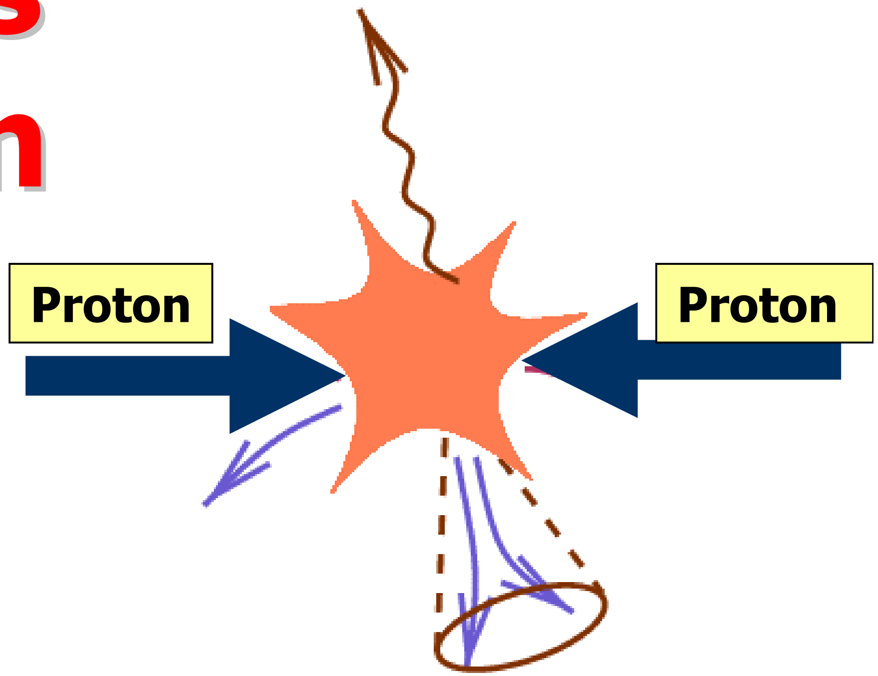
- Usually jet contains one or more π^0 mesons which decay to photons
  - we are really interested in direct photons (from the hard scattering)
  - but what we usually have to settle for is isolated photons (a reasonable approximation)

    Isolation: require less than e.g. 2 GeV within e.g. $\Delta R = 0.4$ cone
- This rejects most of the jet background, but leaves those cases where a single π^0 or η meson carries most of the jet's energy
- This happens perhaps 10^{-3} of the time, but since the jet cross section is 10^3 times larger than the isolated photon cross section, we are still left with a signal to background of order 1:1

There are a number of different technique to distinguish photons from π^0 backgrounds. (see below)

1. Conversion Probability: γ's to convert in a preshower detector
2. Shower Profile: 2 γ's from π^0 will produce EM showers with broader lateral and smaller longitudinal profiles
3. Reconstruction: requires good EM/angular resolution (fixed target)

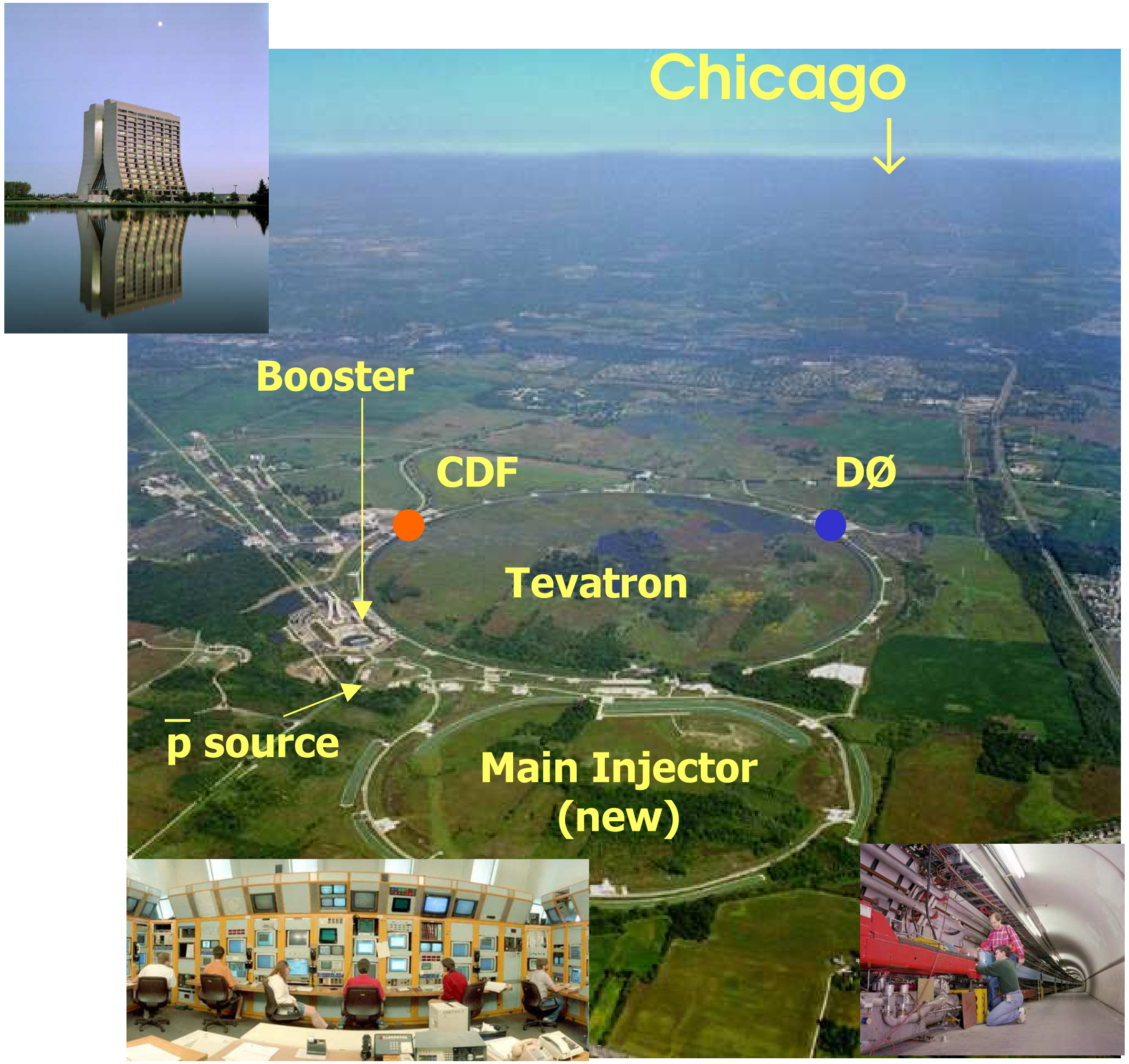
Prompt Photons at Tevatron



Probing QCD

CDF/DØ Background Subtraction Methods
Summary of CDF/DØ Run 1 Photon Results
New puzzles from Tevatron photons
Run II Photon Results, so far…

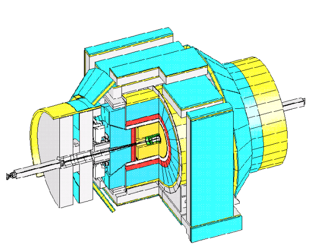
The Fermilab Tevatron Collider



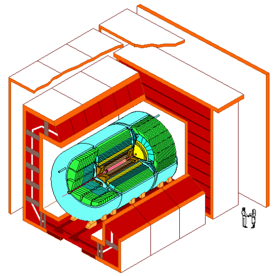
1992-95
- Run 1: 100 pb^{-1}
- 1.8 TeV
- Major detector upgrades

2001-04 ← now (2003)
- Run 2a: 2 fb^{-1}, 1.96 TeV
- Run 2b Upgrade: short shutdown to install new silicon and others

2004-07(?)
- Run 2b: ~ 15 fb^{-1}



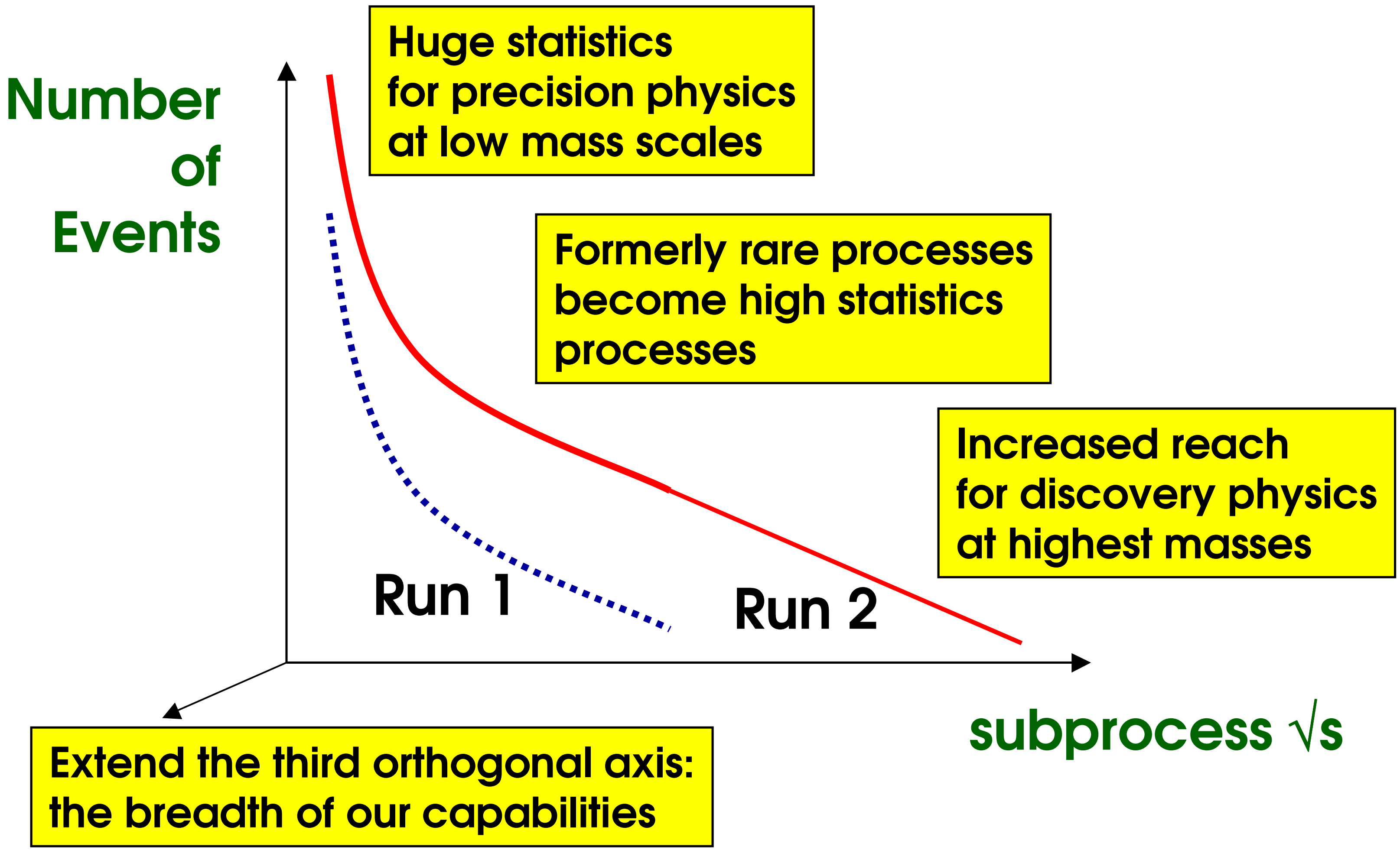
CDF



DØ

Run 1 → Run 2

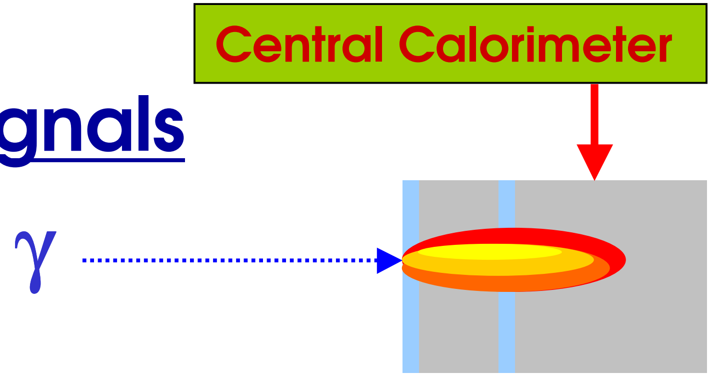
- The TeVatron is a broad-band quark and gluon collider



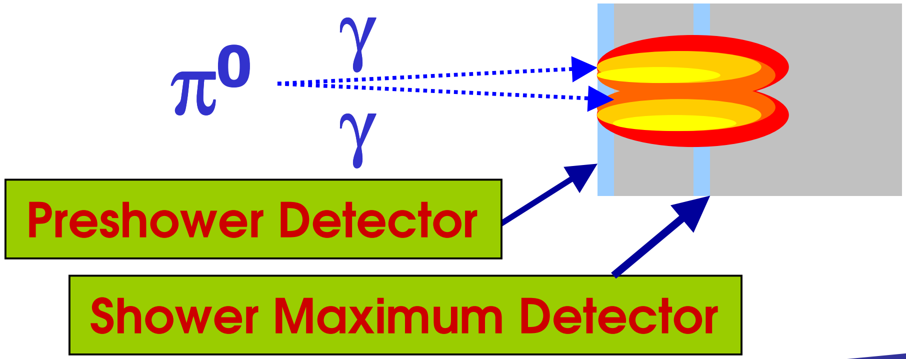
Identification of Photon Signals

Photon candidates: isolated electromagnetic showers in the calorimeter, with no charged tracks pointing at them

- **Signals**



- **Backgrounds**



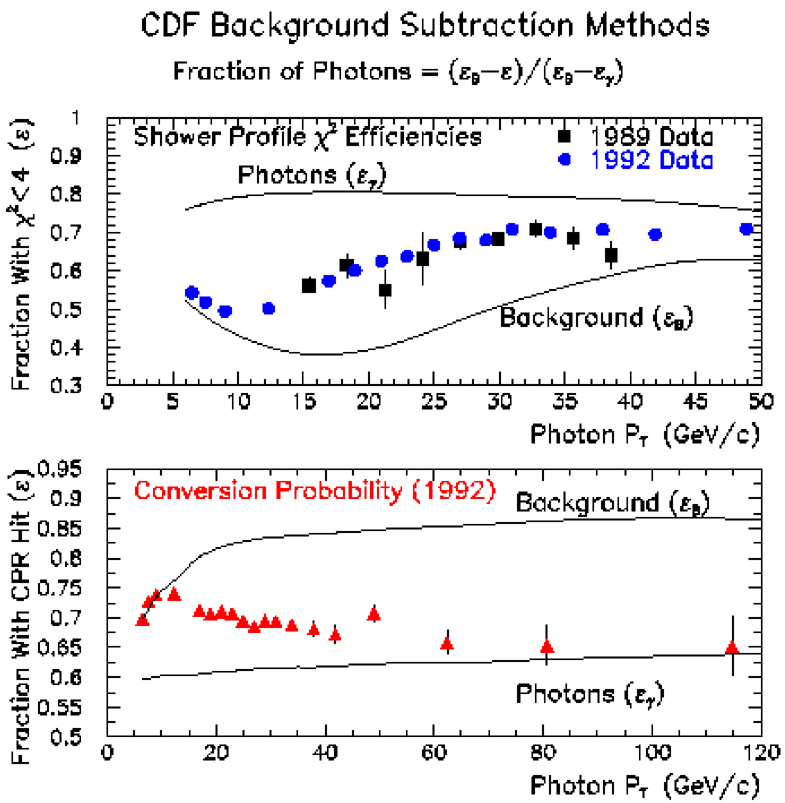
- CDF/DØ uses two techniques for determination of photon signal;
  1. EM Shower width
  2. Conversion Probability
- CDF measures the transverse profile at start of shower (preshower detector) and at shower maximum
- DØ measured longitudinal shower development at start of shower

CES has better separation, CPR better at high Et (Et>35)

	γ-γ	γ-Jet	Jet-jet
CES	24±6%	28±8%	48±7%
CPR	29±23%	40±28%	30±23%

Photon Purity Estimators

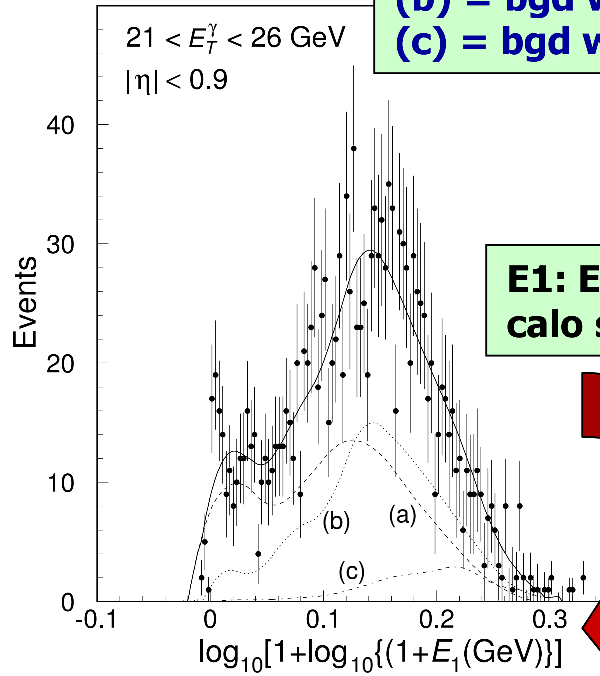
- **CDF**



For every photon, using the conversion and profile info., CDF find the fraction of candidates with this info. (extracted signals statistically)

- **DØ**

Each E_T bin fitted as sum of:
(a) = photons
(b) = bgd w/o tracks
(c) = bgd w/ tracks



E1: E in the 1st calo section

DØ model longitudinal energy depositions of photon's and jets and perform a statistical comparison to data using the discriminant variable to determine the photon purity.

Measurement of Photons in CDF II

Photon Triggers/Dataset

Many Triggers: all are running, including L2 (central/plug photons)

- Inclusive Photon: Et>25, w/ ISO
- Ultra(Super) Photon: Et>50(70)
- Diphoton: Et>12, w/ ISO
- Diphoton: Et>18, w/o ISO
- Triphoton: Et>10, w/o ISO
- Photon: Et>16 + Muon
- Photon: Et>16 + 2 jets (W/Z+γ)
- Photon: Et>10 + SVT track

Many studies started: Backgrounds, calibration, fake rates, simulation…

Large samples are being collected and tested.

Standard Photon ID

Central Photon Cuts:

- Adjust transverse quantities to vertex
- Number of 3-D track
- E fraction b/w HAD and EM Cal.
- Calorimeter Isolation
- Track Isolation
- Two topological shower quantities
  1. EM Shower width
  2. EM Shower cluster energy

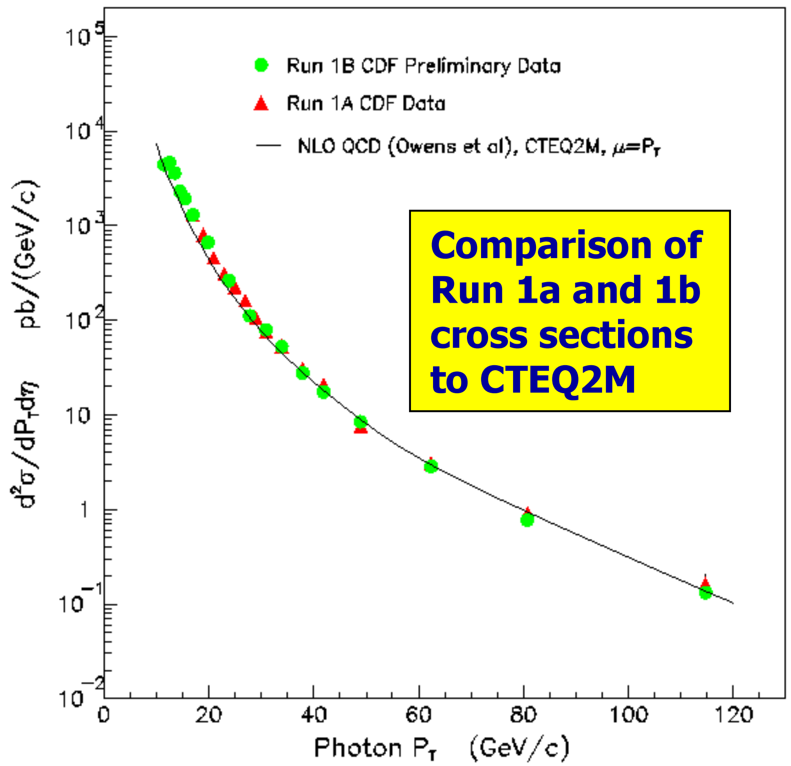
Additional Selections:

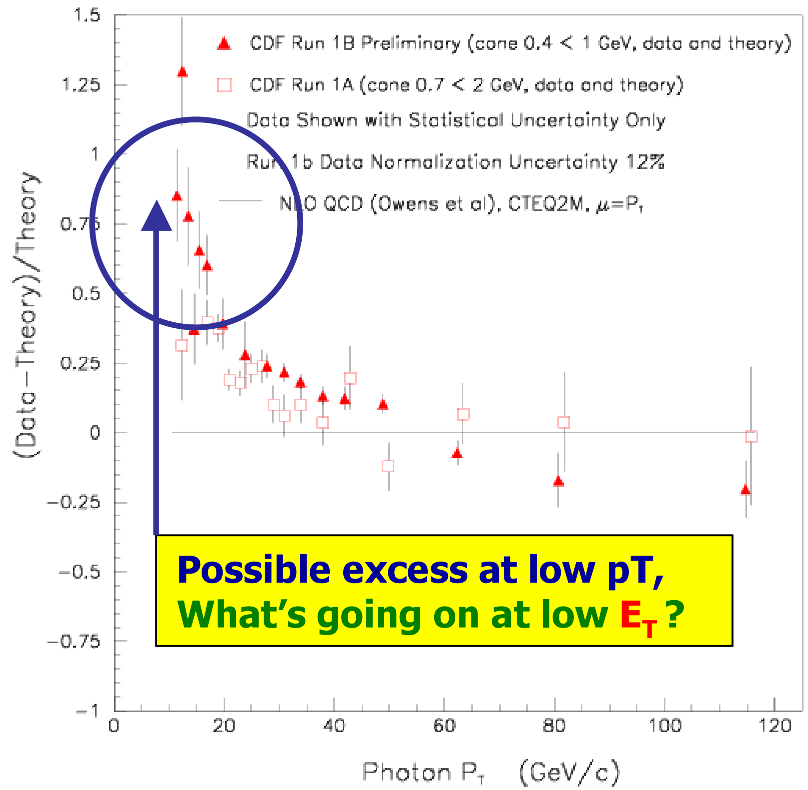
- Cosmic-ray
- Tevatron Beam-Halo events

CDF Photon Cross Sections at 1.8 TeV

- CDF, PRD 65 (2002) 112003

(Data-Theory)/Theory

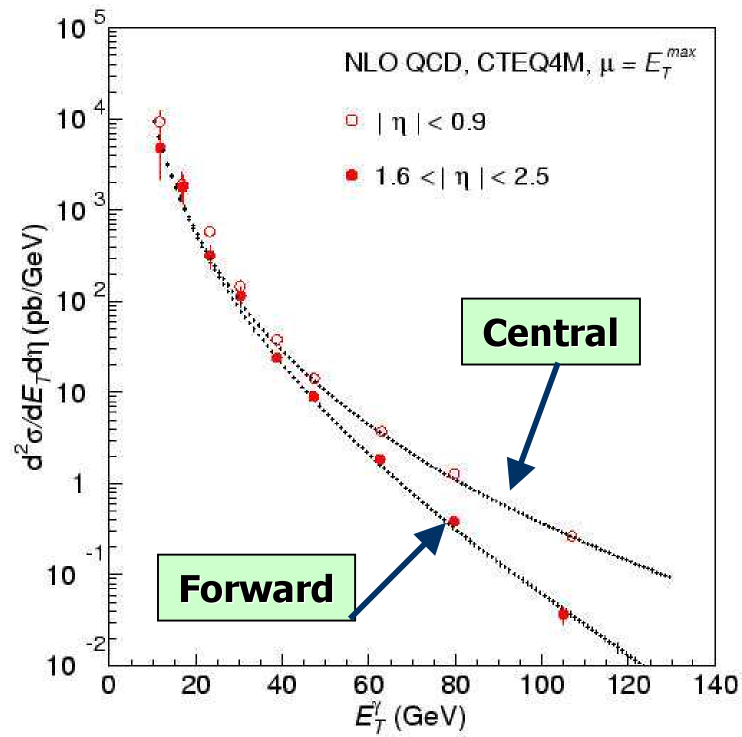




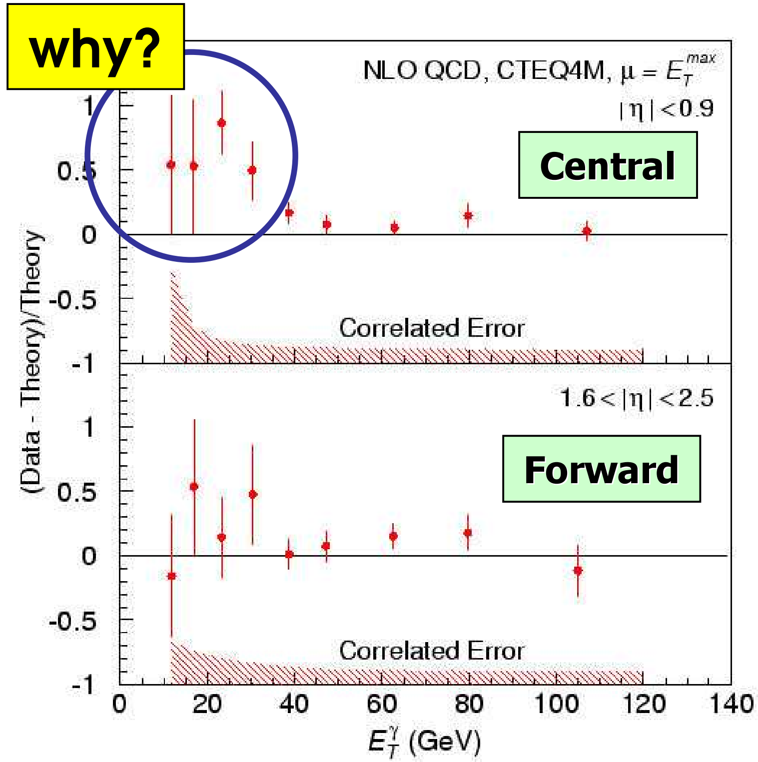
- CDF data from Run 1b agrees with that from 1a and probe both low Et and high Et region in more detail. Results show agreement with NLO, but shape at low p_T is suggestive. What causes the apparent shape at low pT?

DØ Photon Cross Sections at 1.8 TeV

- DØ, PRL 84 (2000) 2786



(Data-Theory)/Theory

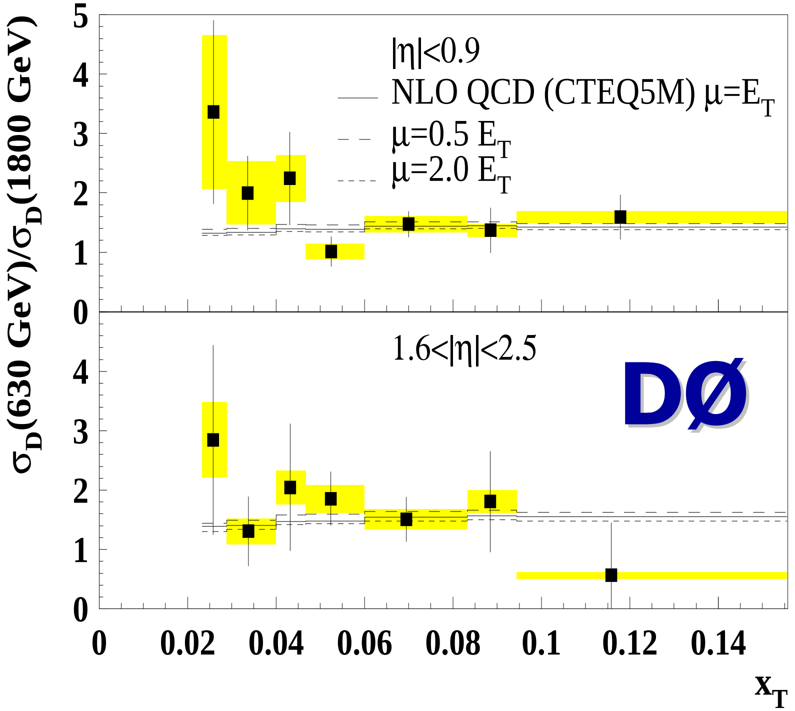


- The measured cross sections is in good agreement with NLO for Et > 36GeV
- The differences between the data and NLO for Et < 36 GeV suggests that a more complete theoretical understanding of the processes is needed.

DØ Prompt Photons at 630 GeV

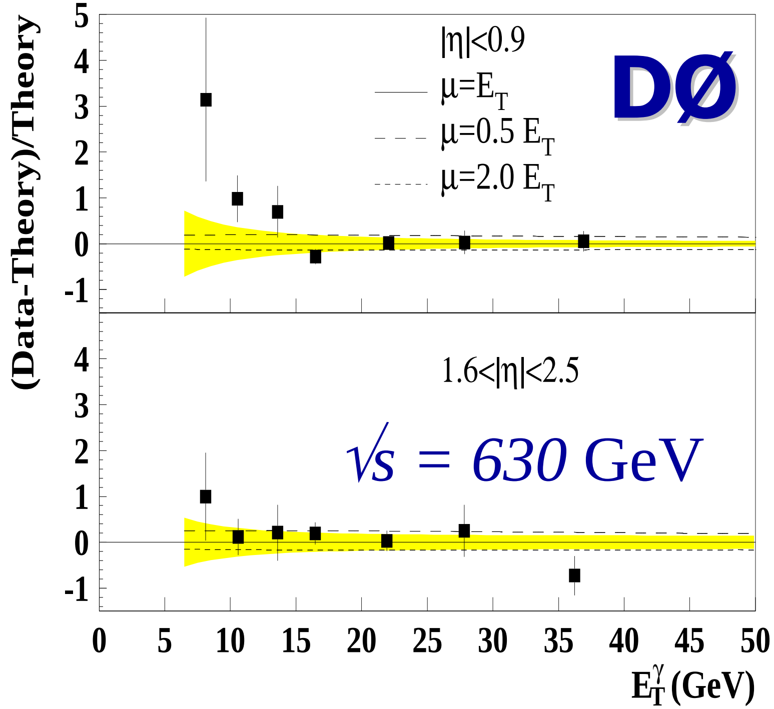
- At the end of Run 1, CDF and DØ both took data at lower CM energy, $\sqrt{s} = 630$
- DØ measured the photon x-sec at 630 and compared to 1800 photon x-sec.

- Low xT deviations are not significant due to experimental uncertainties
- Good overall agreement w/ NLO QCD



DØ, PRL 87 (2001) 251805

(Data-Theory)/Theory



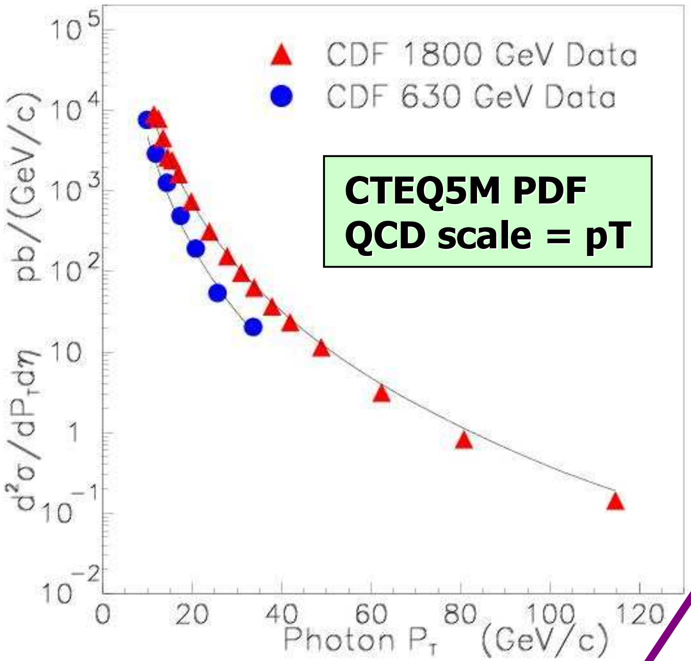
Measurement is higher than NLO at low Et in the central region but agrees at all other Et and in the forward region.

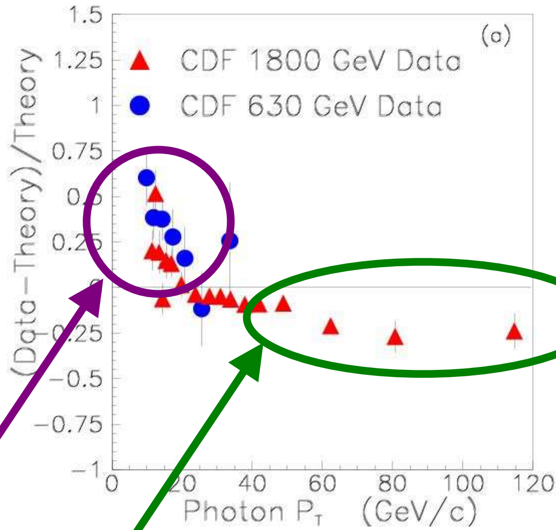
Comparison of Photons at 1.8 TeV and 0.63 TeV

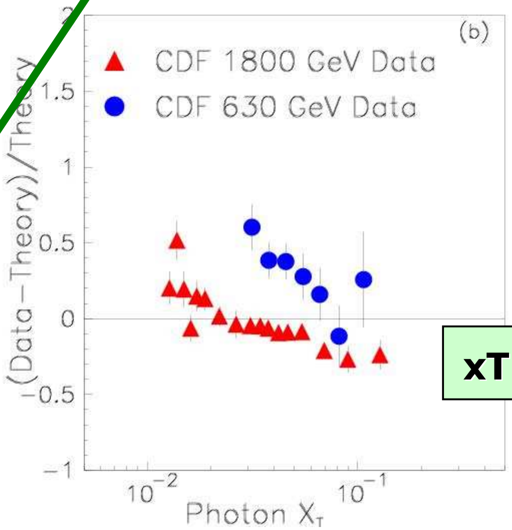
PRD 65, 112003 (2002)

- Inclusive photon cross section at the different √s compared to NLO QCD predictions
- A comparison of the 1.8 TeV and 0.63 TeV data to a NLO QCD as a function of pT and xT

Photon pT and xT







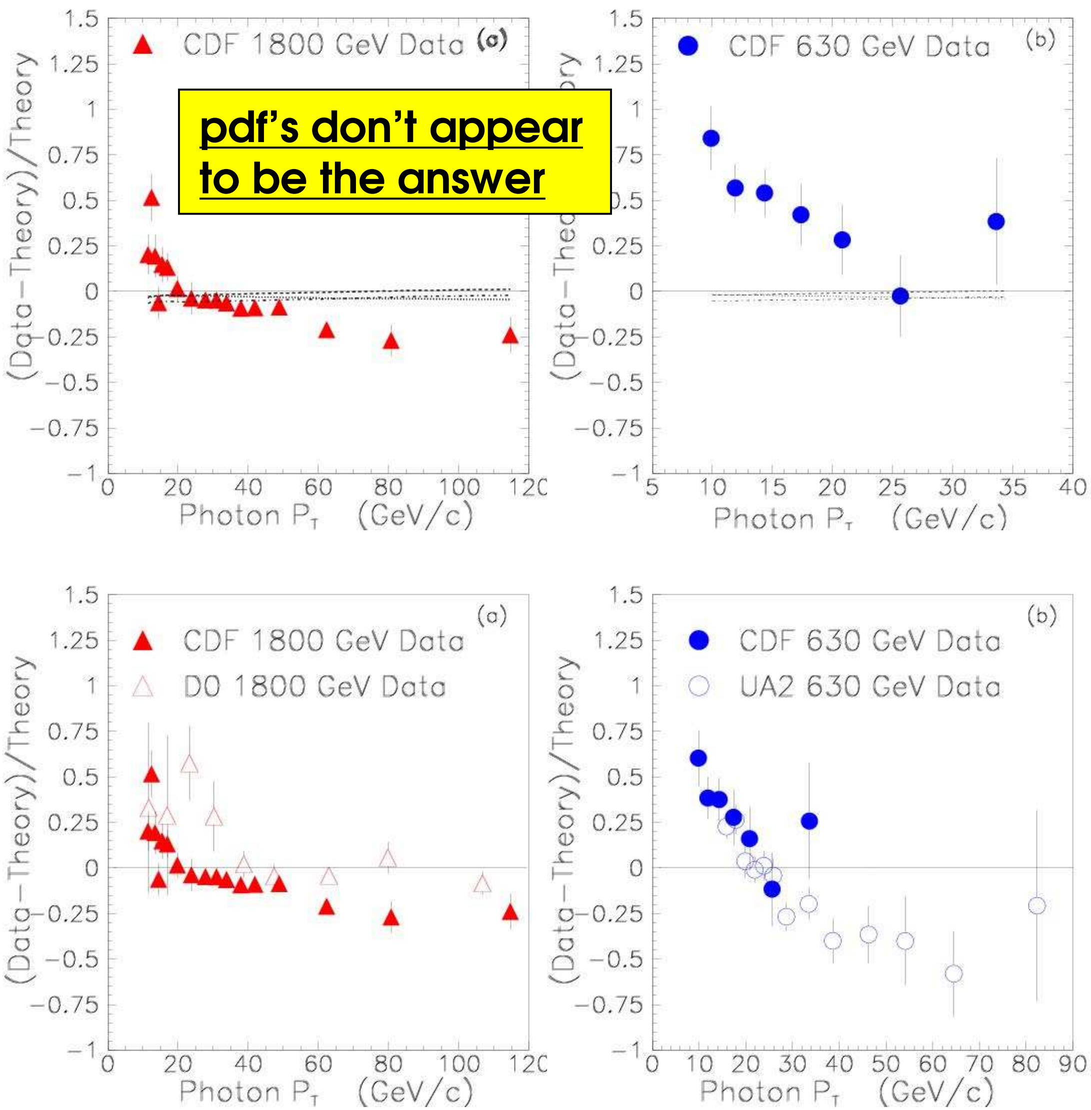
xT=2pT/√s

Deviations from NLO QCD predictions:

→steeper slope at low pT

→normalization problem at high pT at 1.8 TeV

CDF Results consistent those from DØ/UA2



A comparison of the 1.8 TeV and 0.63 TeV cross sections to NLO QCD using different PDFs;

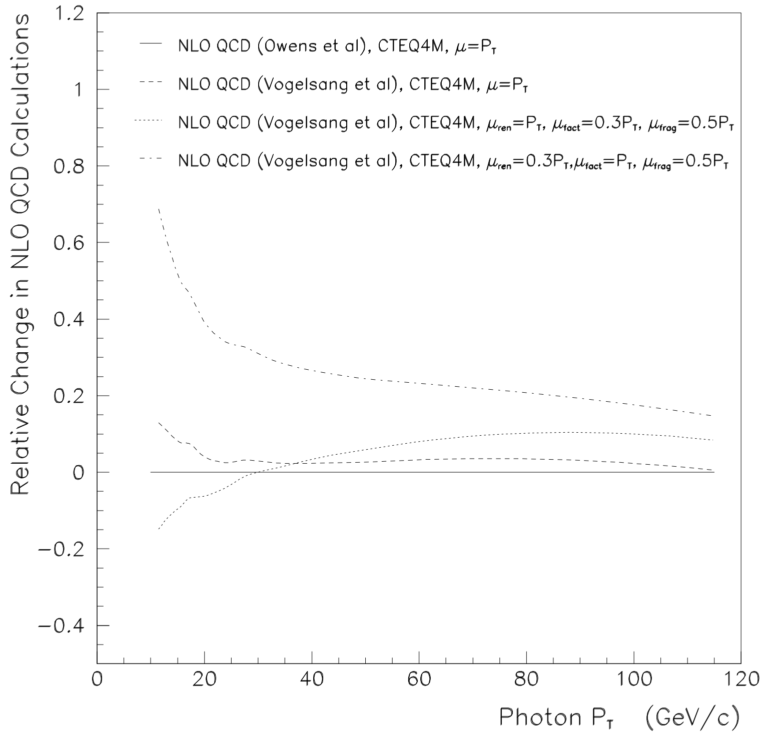
CTEQ5M (Solid)
CTEQ5HJ, MRST99

Many combinations of PDF and scales have been tried and none has been found that match the shape of data

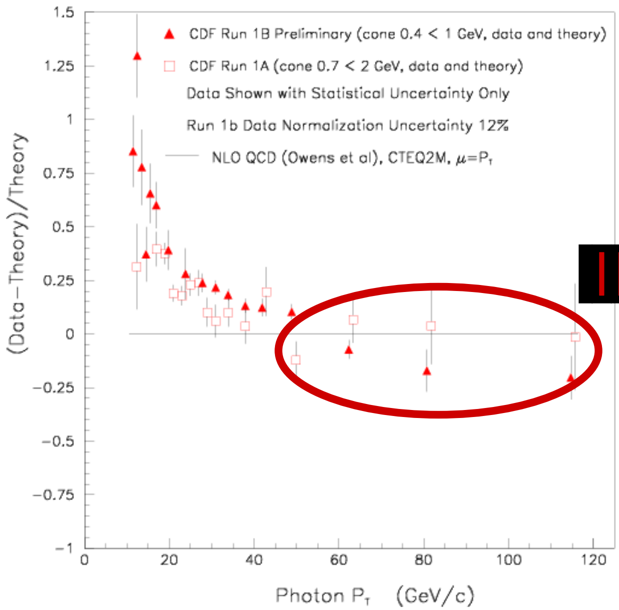
- CDF data agree well with the corresponding D0 and UA2 measurements.
- CDF and DØ data differ in normalization by~20%, consistent w/ systematic uncertainties…

Theory Wiggle Room

Vogelsang et al. have investigated "tweaking" the renormalization, factorization and fragmentation scales separately, and can generate shape differences



Can add some shape to the prediction but hard to get good agreement with data…
And it is "NOT NATURAL" to change the scales so arbitrarily



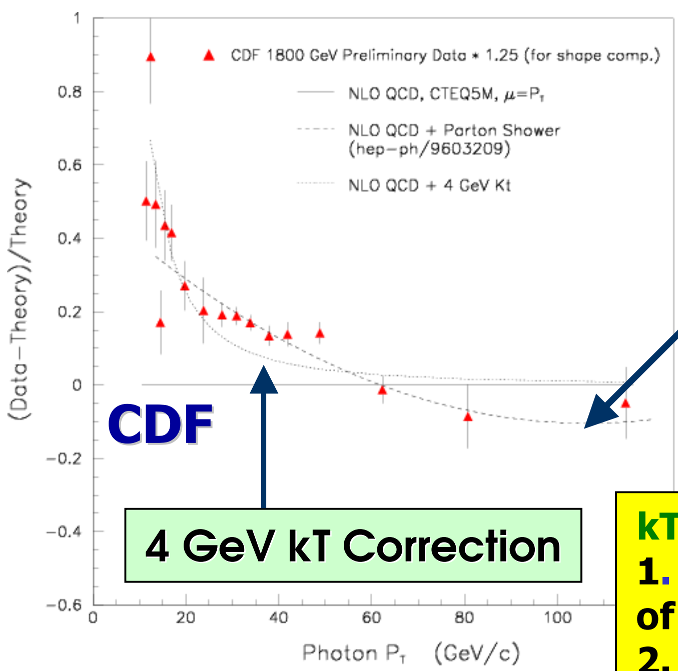
Why is theory larger than data at high pT?

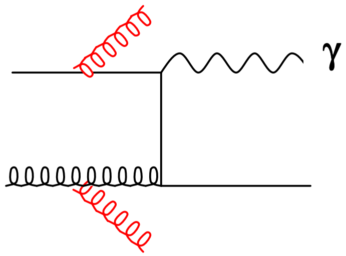
Could soft gluon radiation from initial state by spoiling isolation cut?
→ One of puzzle at the moment…

What's Happening at Low pT?

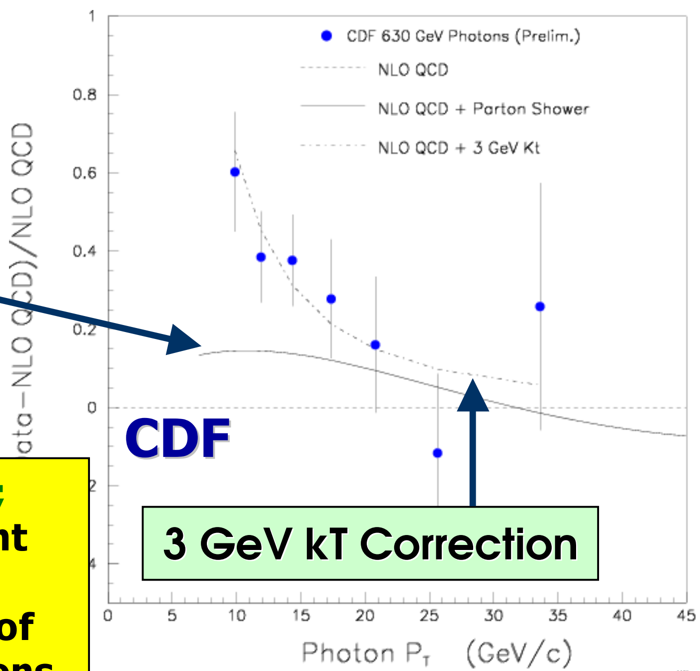
One possibility is an incomplete description of the initial state parton shower in NLO QCD calculation with possible kT recoil effect.
(see k_T Effects in Direct-Photon Production, PRD59 (1999) 074007)

kT denotes the magnitude of the effective transverse momentum of the colliding partons; Gaussian smearing of the transverse momenta by a few GeV can model the rise of cross section at low E_T





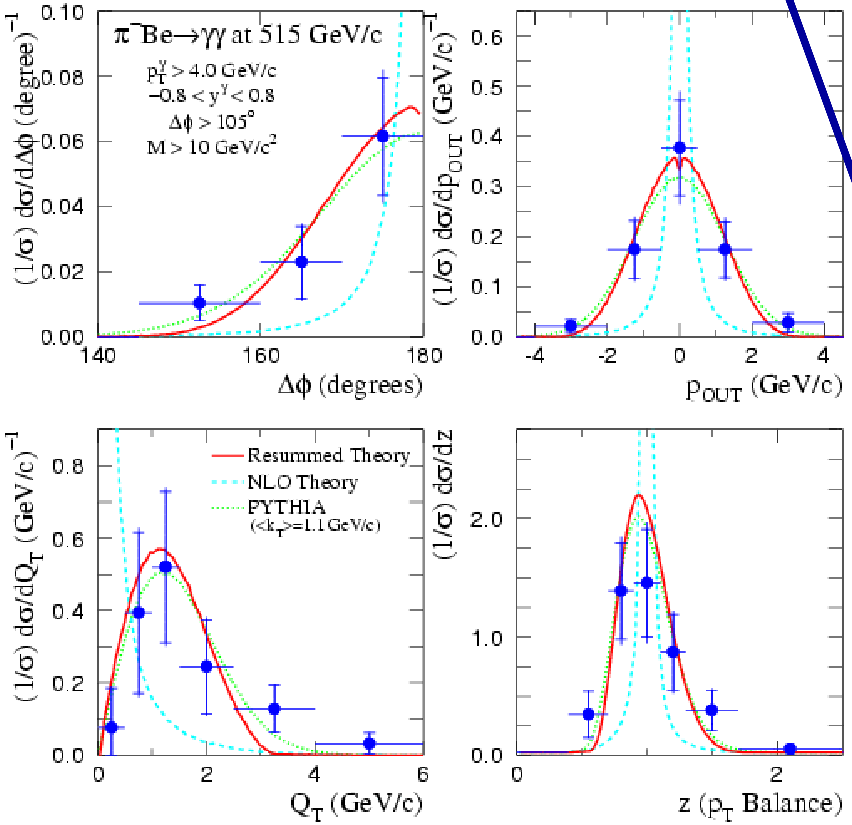
Parton shower (Baer and Reno)

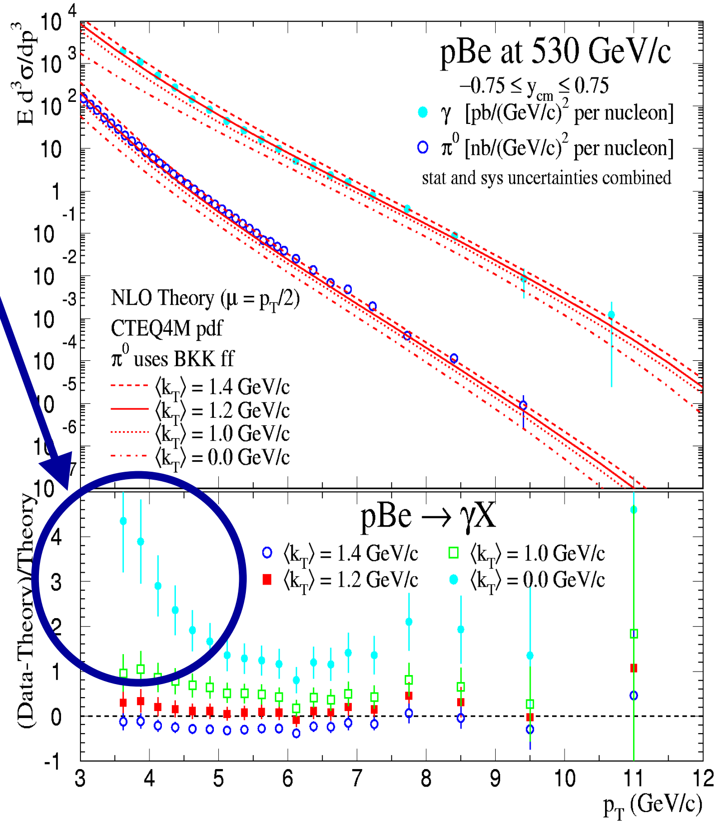


kT is expected to modify;
1. back-to-back alignment of final state objects,
2. magnitude and shape of high pT inclusive x-sections

Fixed Target Photon Production

- Fixed target experiment (E706) sees the largest disagreement with NLO



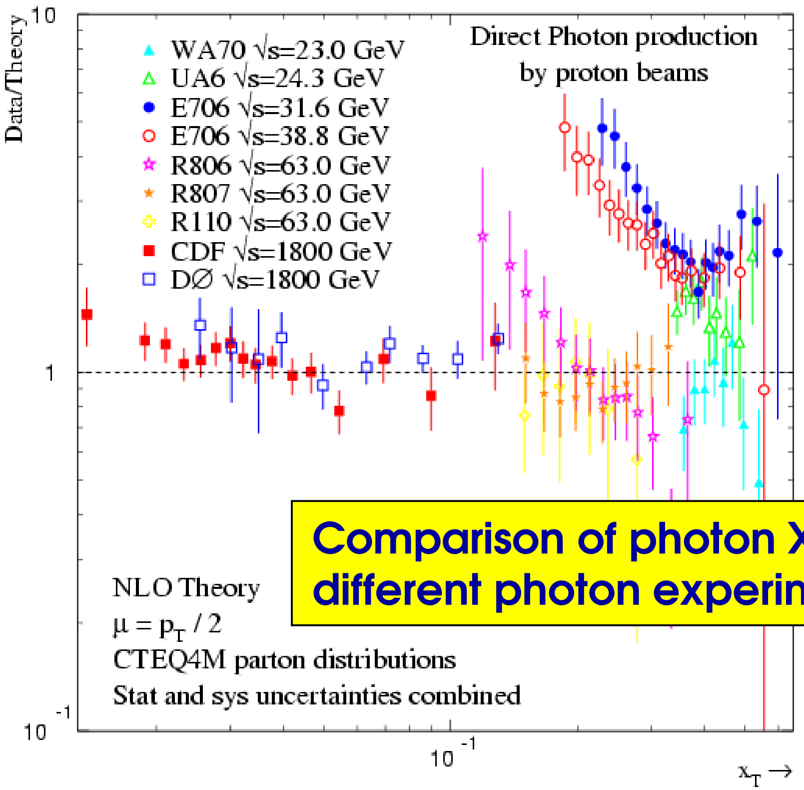


- ❑ Again, Gaussian smearing (~1.2 GeV) can account for the data.
- ❑ Theoretical uncertainties are too large to use prompt photons to determine the gluon distribution.

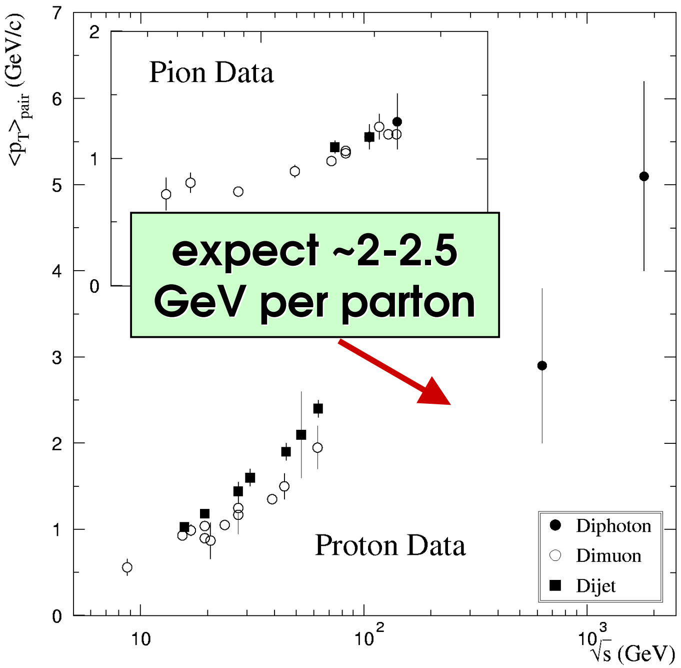
Direct Photons and Parton k_T

- The Tevatron exp. highlight serious limitations of current QCD description of prompt photon production
- One offered explanation is that the partons in the proton may have a considerably higher kT due to soft gluon radiation at low pT

- $\langle k_T \rangle$ increase as approximately logarithmic with $\sqrt{s}$
  - 1 GeV for fixed target
  - 2.5 GeV at $\sqrt{s}$ = 630 GeV
  - 3~4 GeV for TeVatron at $\sqrt{s}$ = 1.8



Comparison of photon XT for different photon experiments

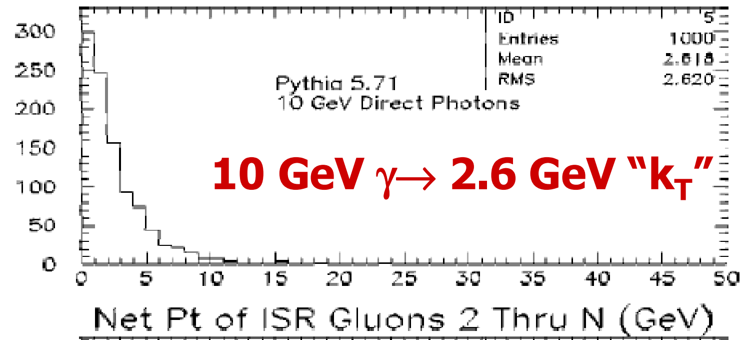


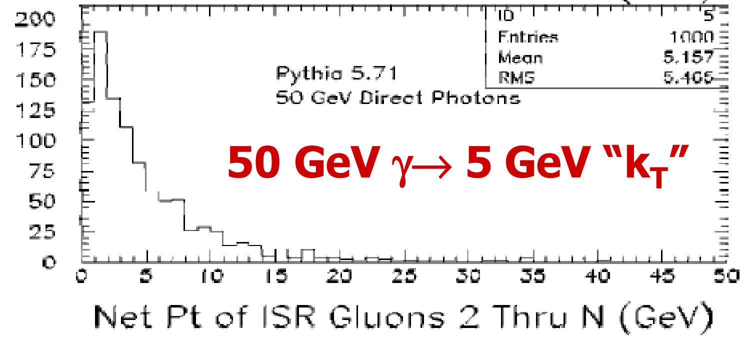
Gaussian smearing of kT gives good agreement with Tevatron photon data

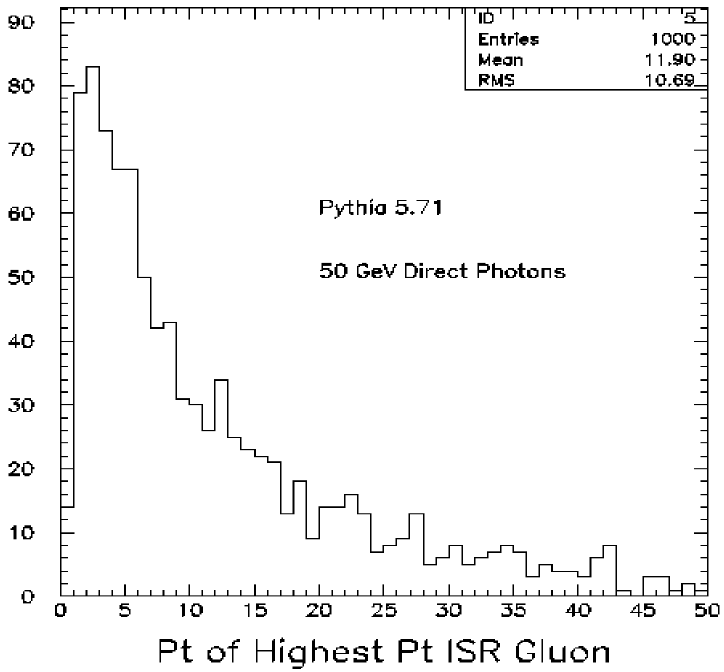
Why would you need to do this?

- Study the number and pT of Initial state gluons w/ PYTHIA MC

•pT recoil values of 2-4 GeV may cause smearing of the measured direct photon falling pT spectrum.
•…but only matters if the effect is not completely included in the model considered, typically NLO QCD







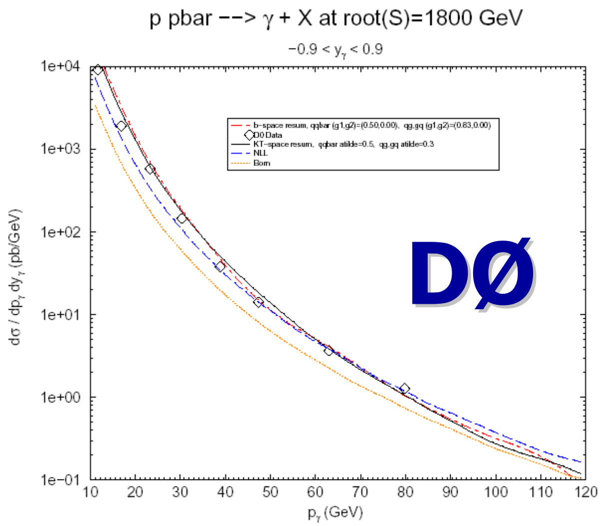
In PYTHIA, find that additional gluons add an extra 2.5–5 GeV of p_T to the system (2-3 GeV at 630 GeV – not shown)

Resummation

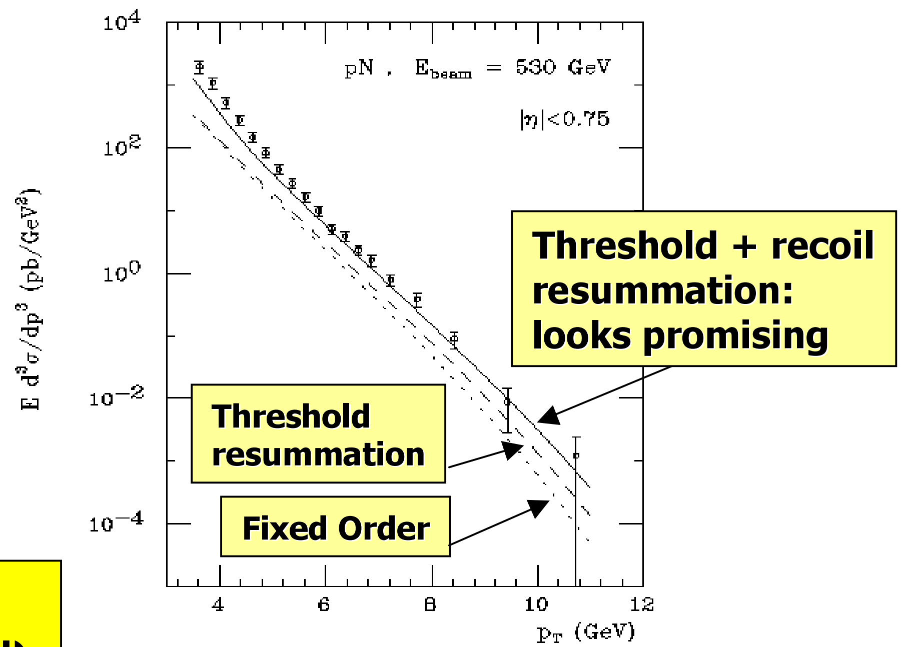
Calculation using pT resummation of initial state gluons are on the horison..

- Redictive power of Gaussian smearing is small
  - e.g. what happens at LHC? At forward rapidities?
- The "right way" to do this should be resummation of soft gluons
  - this works nicely for W/Z $p_{T,}$ at the cost of introducing parameters

Fink and Owens
hep-ph/0105276



Laenen, Sterman, Vogelsang,
hep-ph/0002078

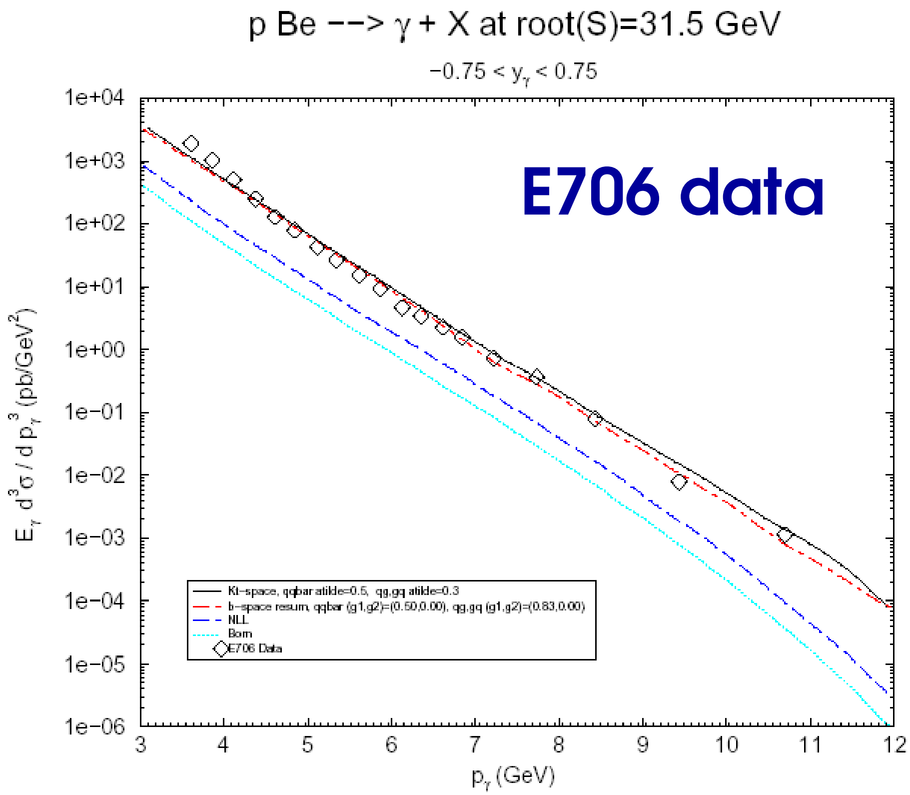


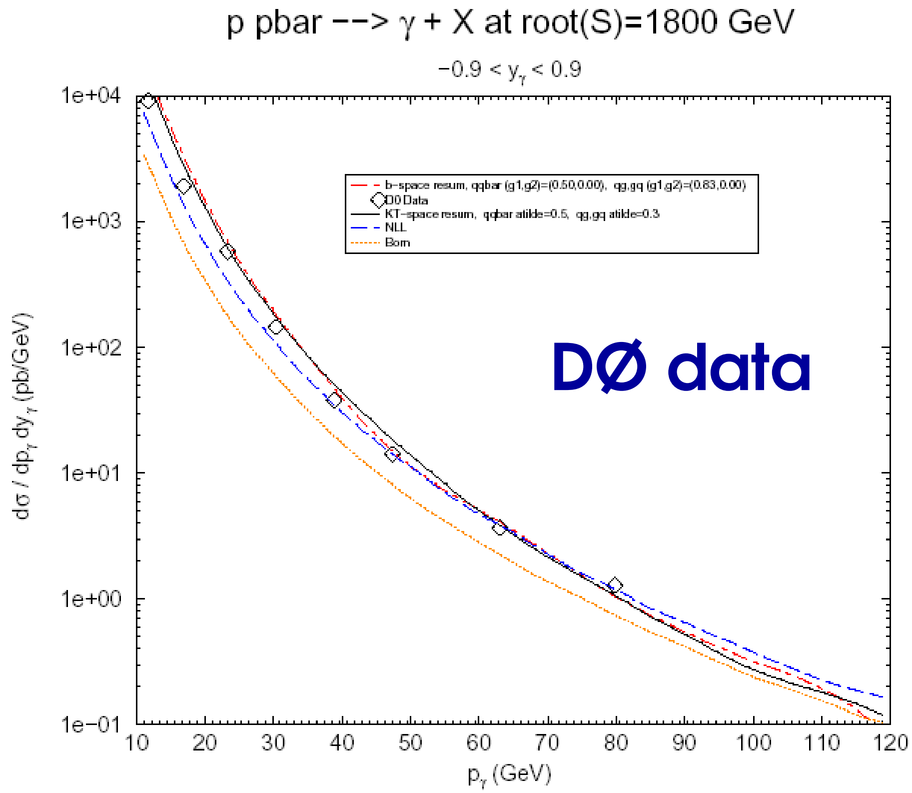
Agreement with data is pretty good now (Theory has improved!!)

Fink and Owens Resummed Calculations

- hep-ph/0105276

Calculation using pT resummation of initial state gluons are on the horison..



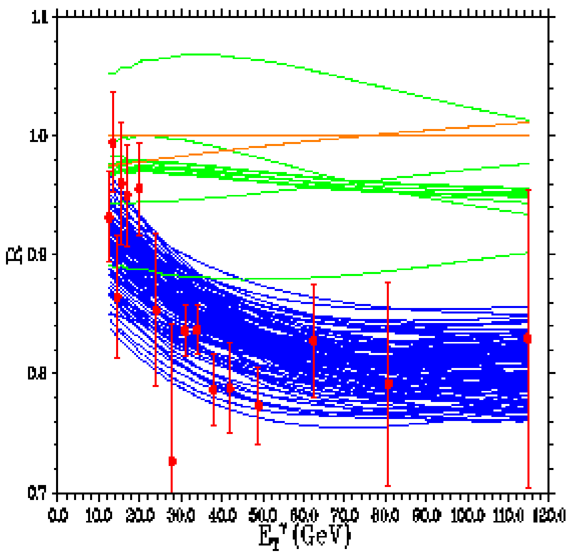


Agreement with data is pretty good

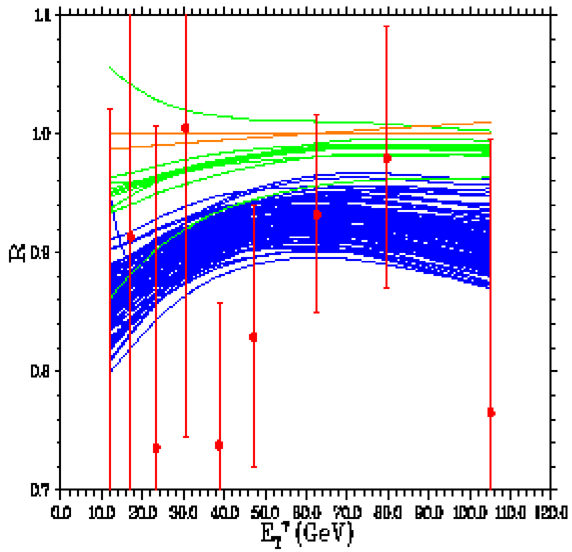
Does require 2 or 4 non-perturbative parameters to be set

Is It just the PDF?

- New PDF's from Walter Giele can describe the observed photon cross section at the Tevatron without any k_T, and predict the "deficit"



CDF (central)



DØ (forward)

Blue = Giele/Keller sets
Green = MRS99 set
Orange = CTEQ5M and L

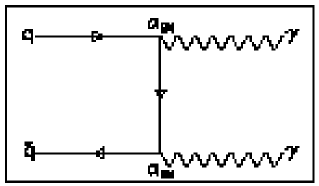
Not all of Walter's PDF sets have this feature: it depends on what data are input

TeVatron Diphoton Productions

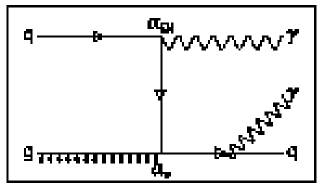
- Rate is very small: few hundred events in Run I ($p_T > 12$ GeV)

- But interesting because
  - final state kinematics can be completely reconstructed (mass, p_T and opening angle of $\gamma\gamma$ system)
  - background to $H \to \gamma\gamma$ at LHC

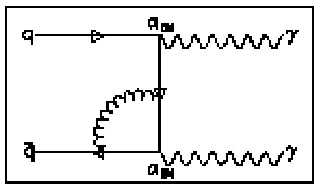
- NLO calculations available



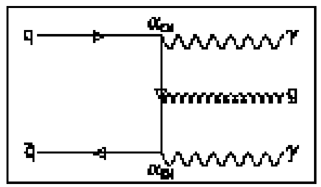
Born Diagram



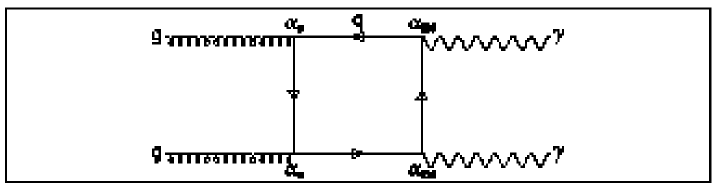
Bremstralung



Virtual Process



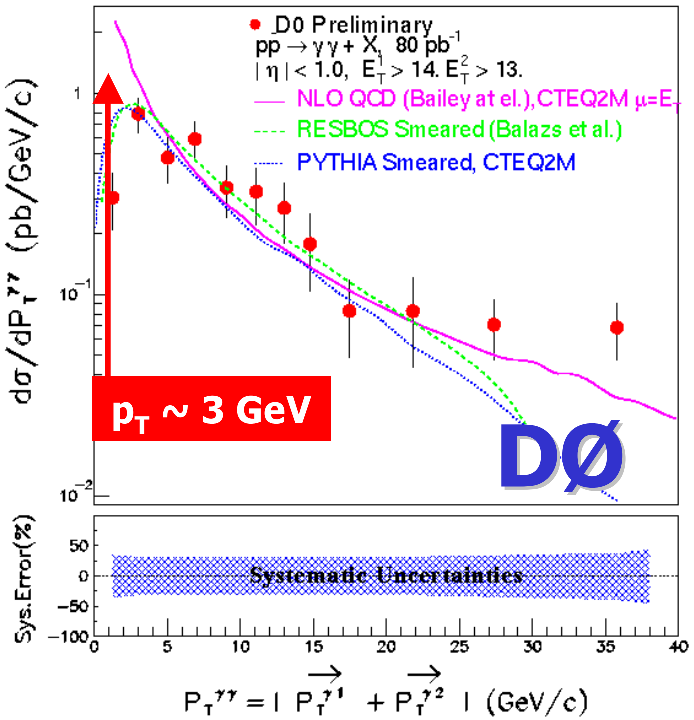
Soft Gluon Emission



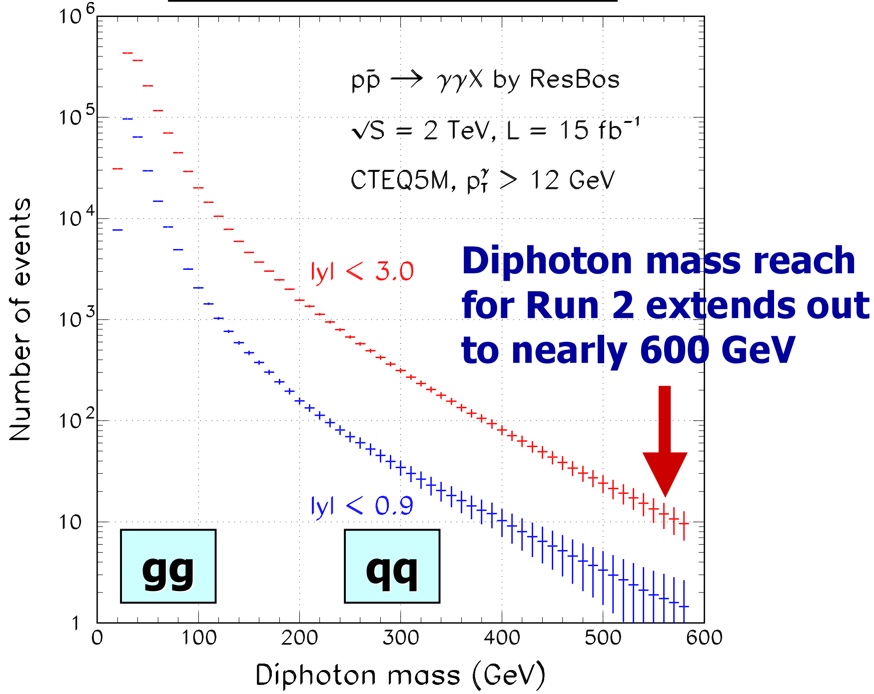
Box Diagram

Diphoton Production at the Tevatron

- Diphoton production is interesting both for QCD tests and searches for new phenomena, but rate is very small (few hundred events in Run I)
- The final state kinematics can be completely reconstructed (mass, p_T and opening angle of $\gamma\gamma$ system)



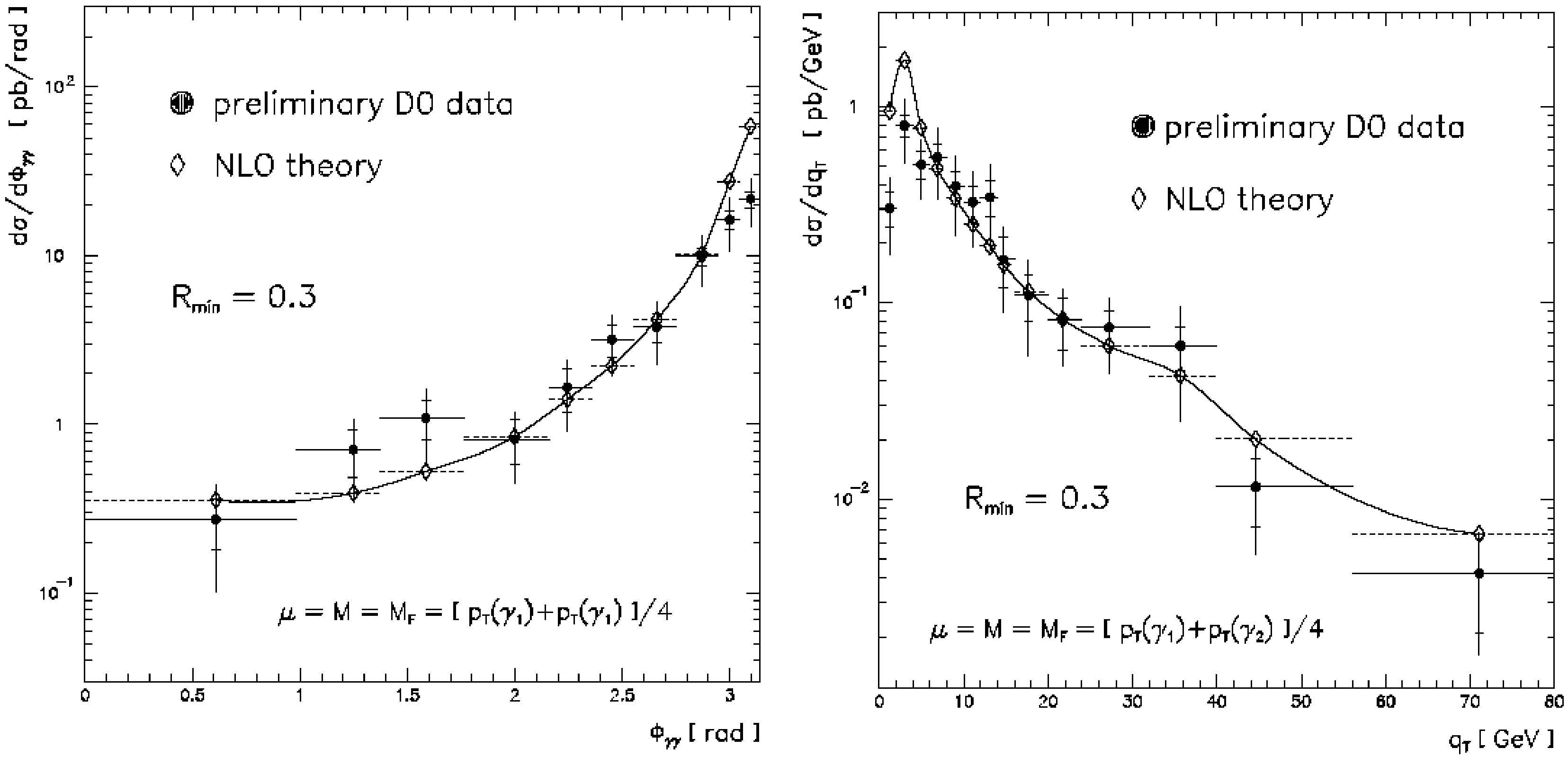
Run 2 Prospects



- Need a resummation approach (RESBOS) or parton shower MC (PYTHIA) or ad hoc few-GeV k_T smearing

Latest NLO Diphoton Calculation

- Binoth, Guillet, Pilon and Werlen, hep-ph/0012191



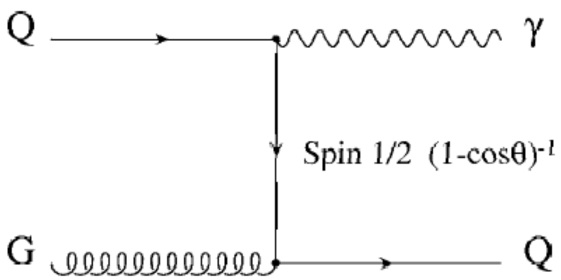
Shoulder at 30 GeV in calculation is a real NLO effect (contribution opens up with both photons on same side of the event)

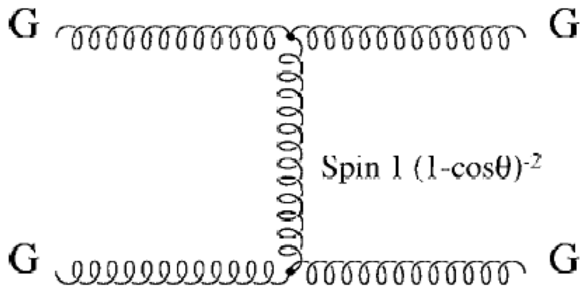
Photon + Jet Angular distributions

Unique test of pQCD

The dominant process producing photons

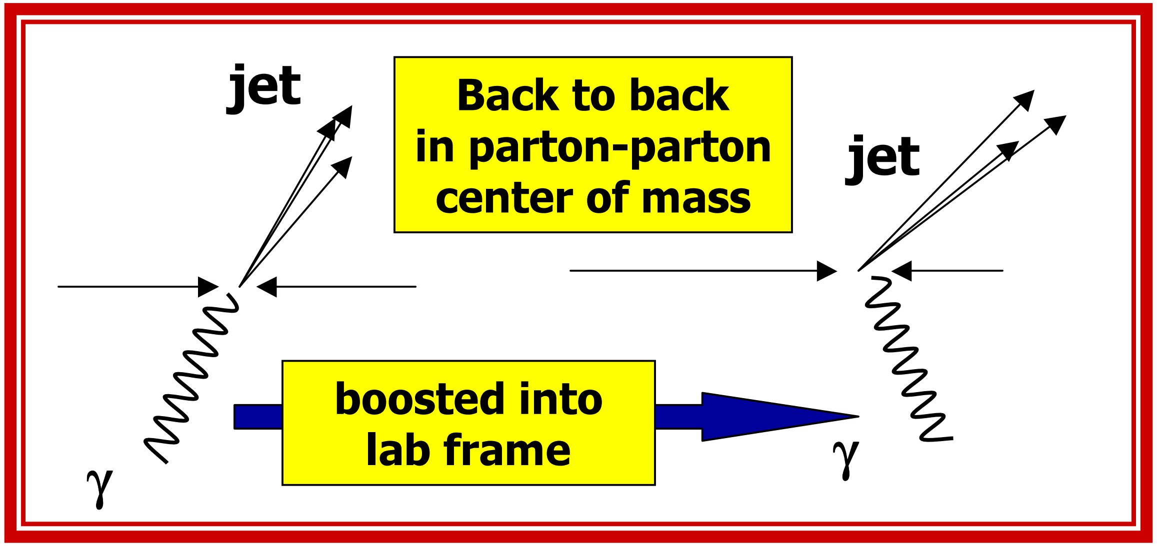
Should be quite different from dijet production:

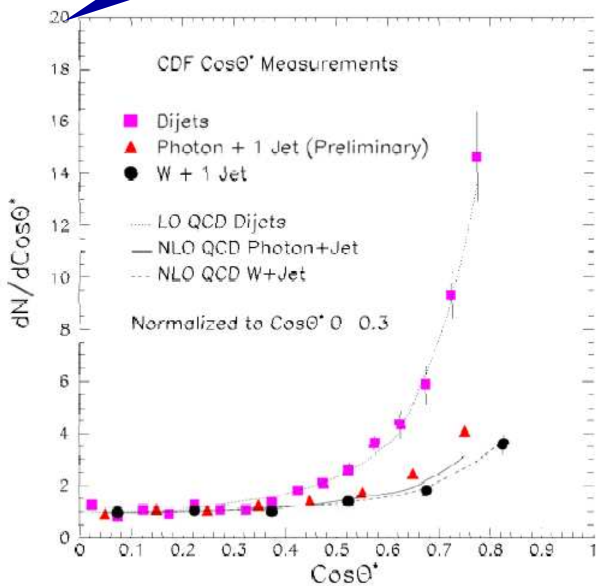




Excellent agreement between OCD and Data…

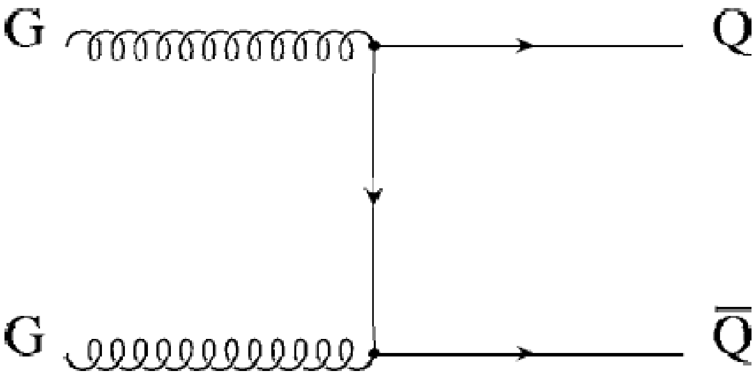
Can we test this?





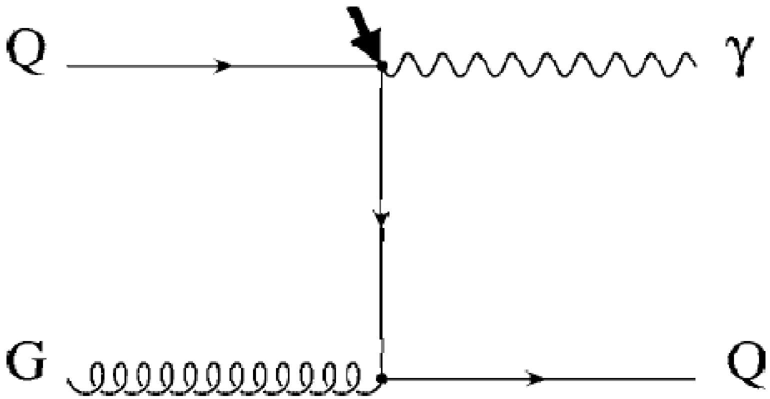
Photons as a probe of quark charge

- Inclusive heavy flavor production "sees" the quark color charge:



In semileptonic decays of heavy quarks, bottom quark fraction is enhanced by harder fragmentation and sequential decays of the charm

- While photons "see" the electric charge:



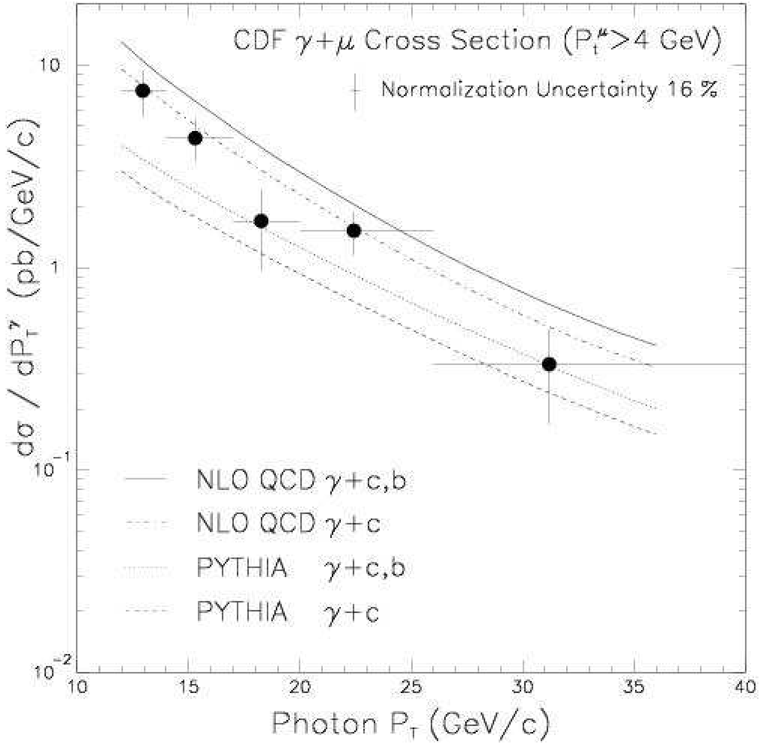
Photon vertex sensitive to electric charge.

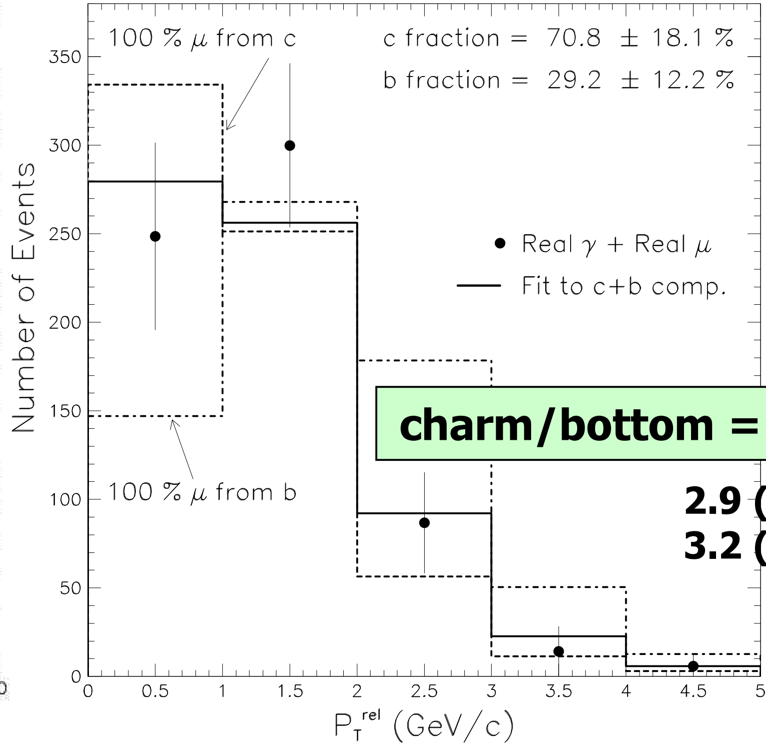
Back to a photon sample, use the classic "pT relative" technique to separate final state charm and bottom.

CDF Photon + Heavy Quark

- The 1st measurement of Heavy flavor contents of associated photon+μ events
- The events are due to Compton Scattering process cg->c(->μ) + γ

PRD 65, 012003 (2002)





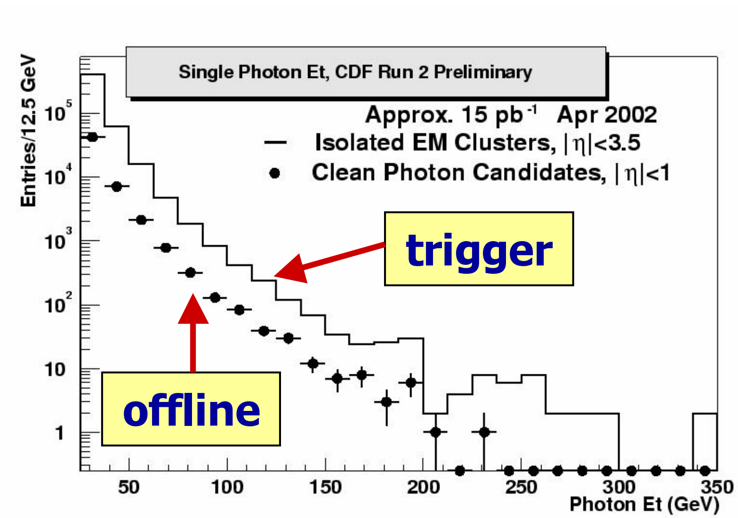
charm/bottom = 2.4 ± 1.2

2.9 (PYTHIA)
3.2 (NLO QCD)

The shape of the data agree with theory predictions, but fall below the theory in normalization by 2 standard deviations.

A significant fraction of the events contain a final-state b quark. The ratio of c to b is in good agreement with QCD

Run II CDF Photons

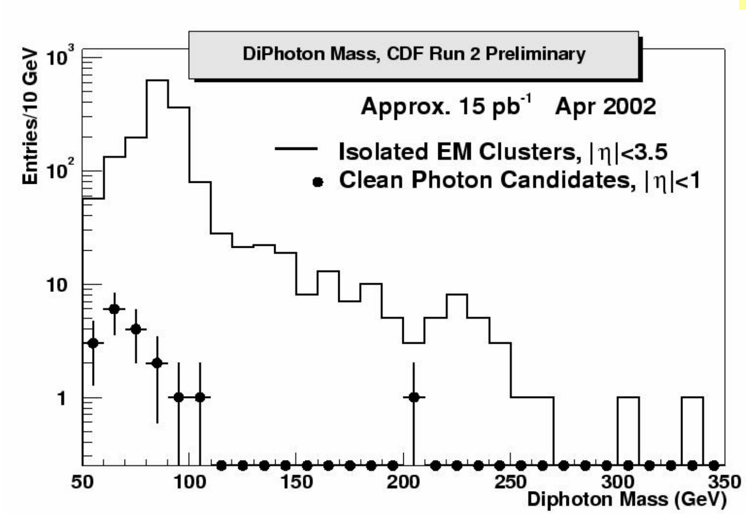


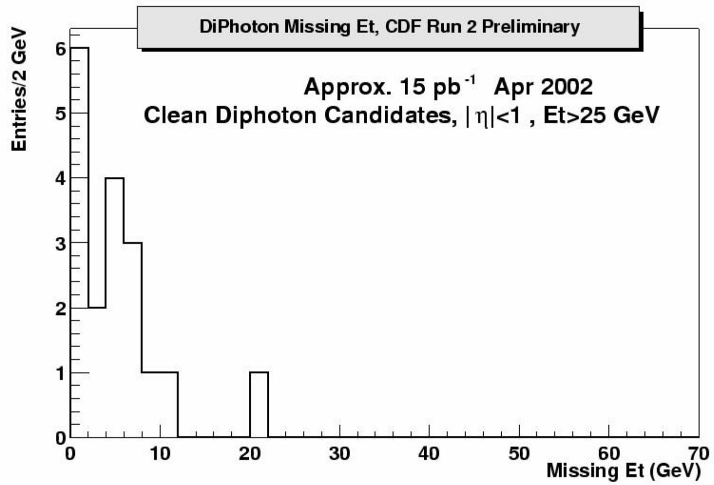
Data from Aug 8 – Apr 5 (15 pb^{-1})

Inclusive photon sample
- cal/tracking Iso, HAD/EM cuts
- results are similar to Run 1B

Inclusive diphoton sample
- require 2 photons
- same requirement as single photon

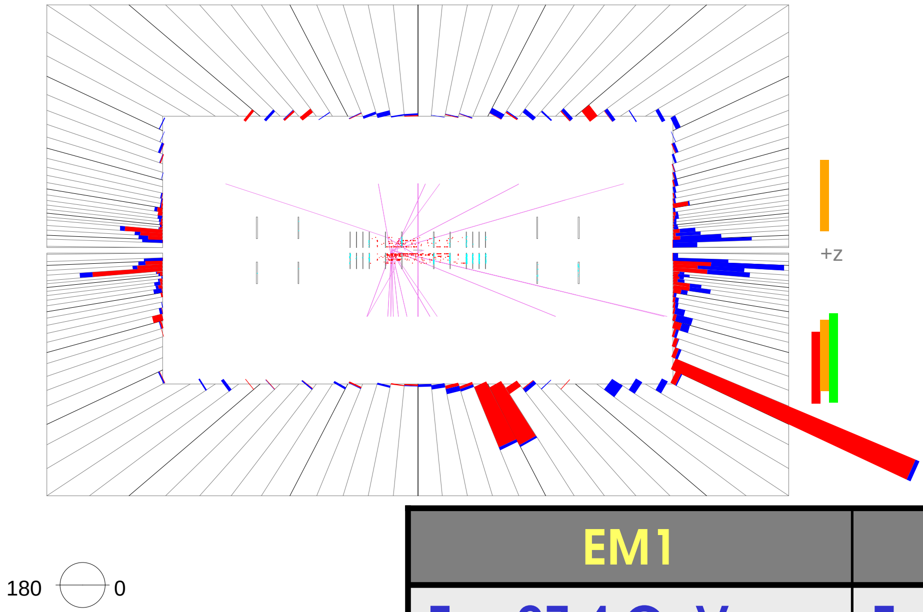
Diphoton is an interesting QCD measurement but is also a great place to look for new physics

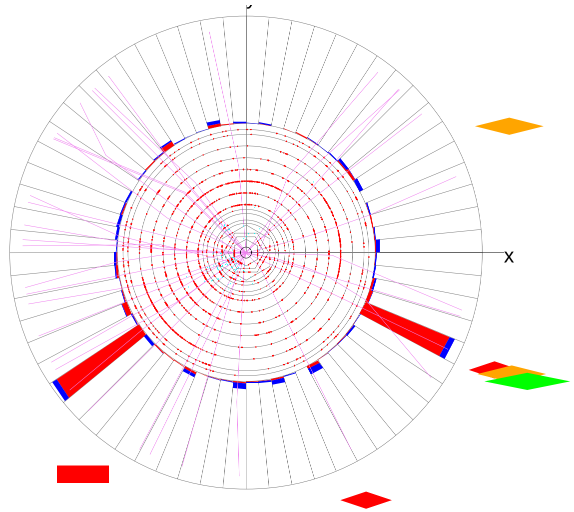




Run 2 Missing E_T + di-EM Candidate

$\gamma\gamma$+MET is a signature of gauge-mediated SUSY-breaking

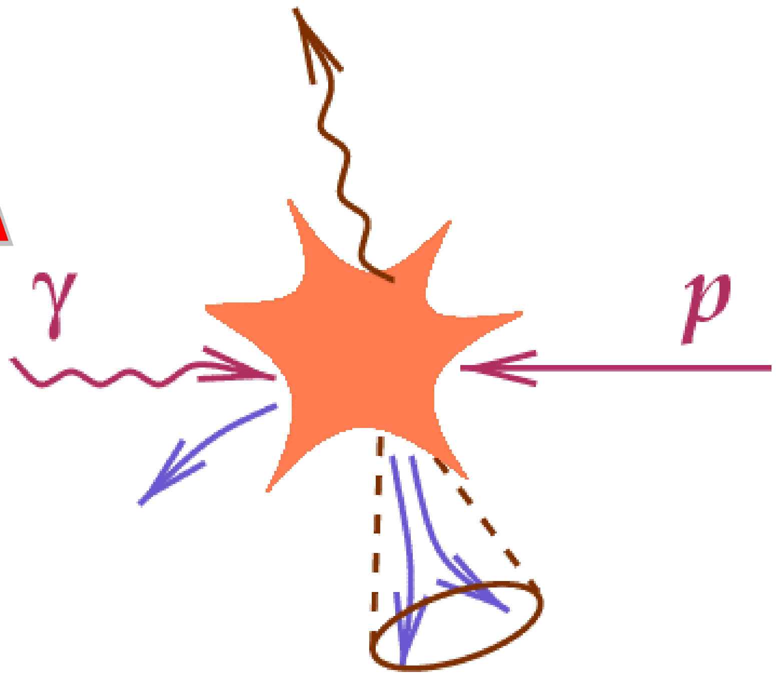




EM1	EM2
E_T = 27.4 GeV	E_T = 26.0 GeV
η = 0.52	η = 1.54
φ = 3.78	φ = 5.86
Loose match with a low-p_T track	No track match
ME_T = 34.3 GeV; M(diEM) = 53 GeV	

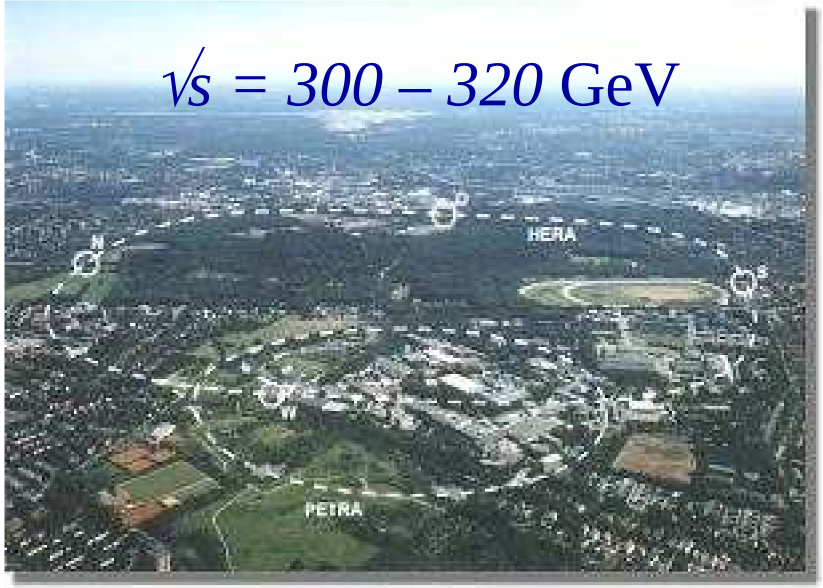
Prompt Photons at HERA

Probing QCD



Background Subtraction Methods
Summary of ZEUS Prompt Photon Results
ZEUS Determination of Parton kT
New H1/ZEUS Photon Results – Preliminary

DESY HERA Collider



First electron(positron)-proton collider in the world, Hamburg, Germany

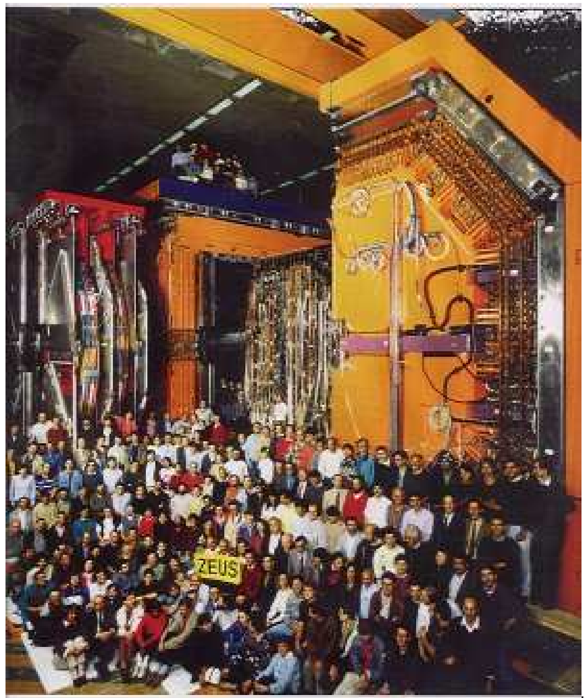
27.5 GeV electron + 920 GeV proton

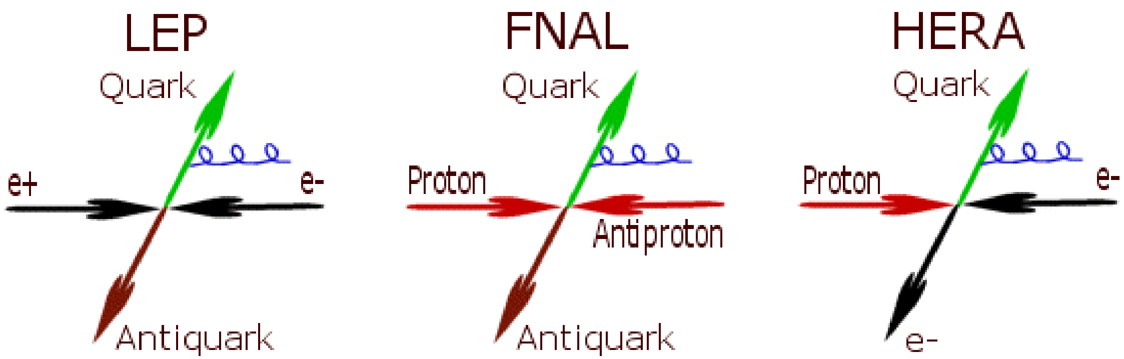
Circumference: 6.336 km

4 exp: ZEUS, H1, HERMES and HERA-B

Data ~130 pb^{-1}/expt. 2006~1 fb^{-1}/expt.

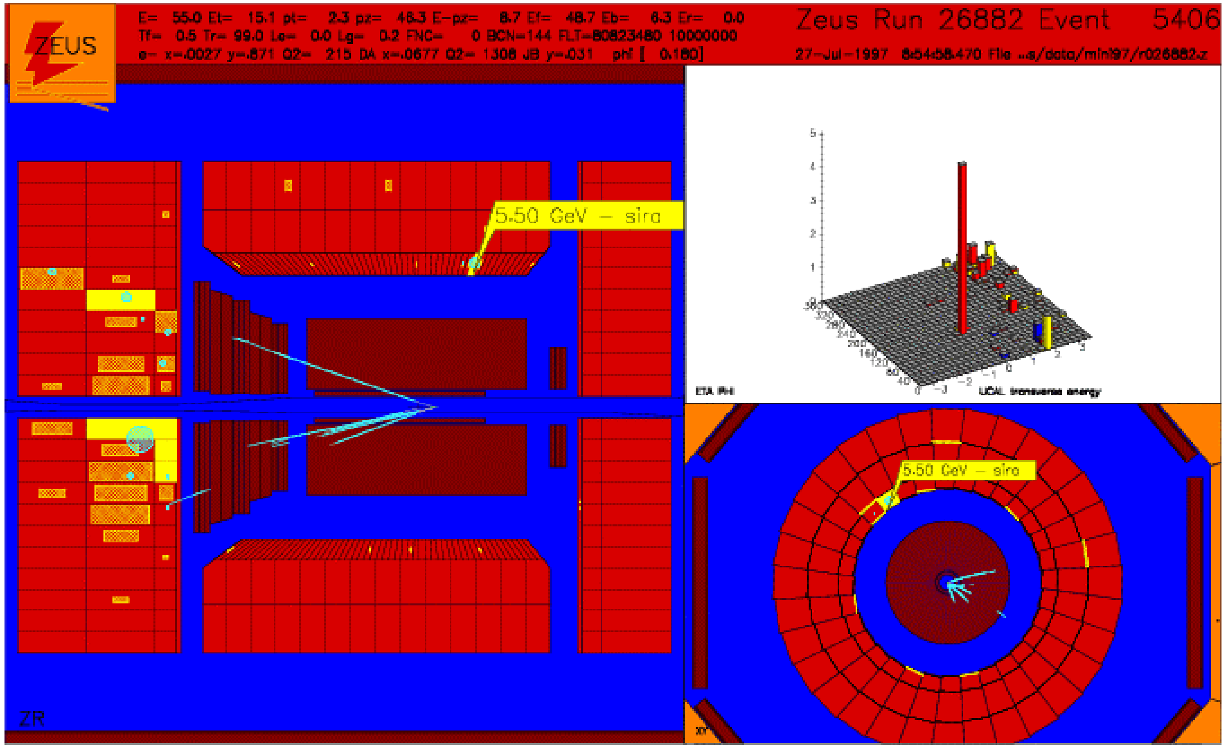
ZEUS Collaboration





e^+p: 1994-2000 and e^-p: 1998-1999

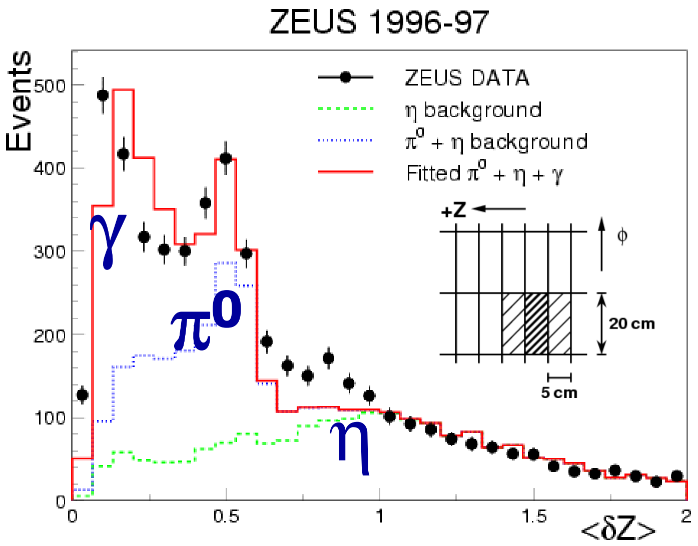
Prompt Photon Measurement at HERA

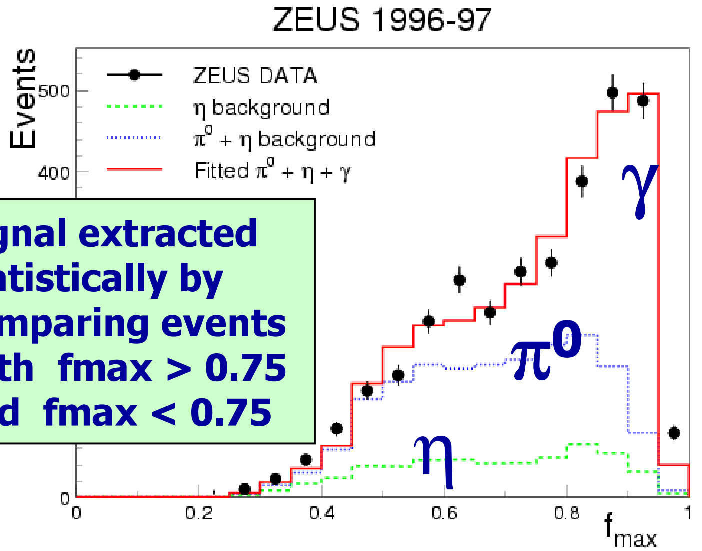


- Example of prompt photon production in the direct process at ZEUS
  - Clearly identified in calorimeter and well isolated
  - ZEUS BCAL has good granularity to separate high ET photon from neutral pion and eta meson backgrounds
- Potentially significant backgrounds from jet fragments in dijet
  - Isolation cuts and Shower shape cuts are required to remove these

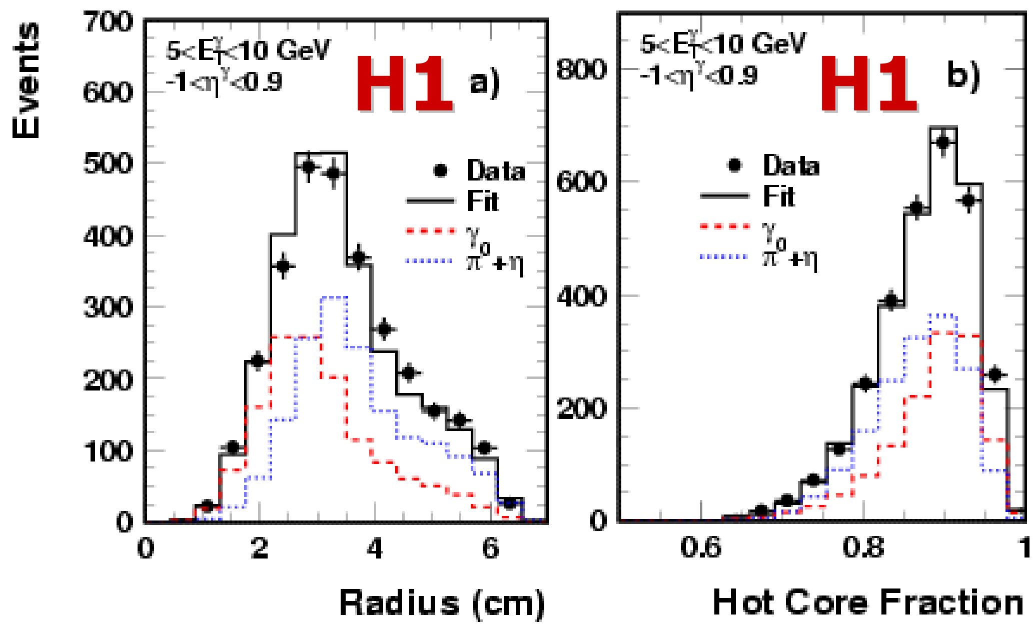
Identification of Photon Signal at ZEUS/H1

Topological shower shape quantities are used to separate 2 nearby photons





Signal extracted statistically by comparing events with fmax > 0.75 and fmax < 0.75



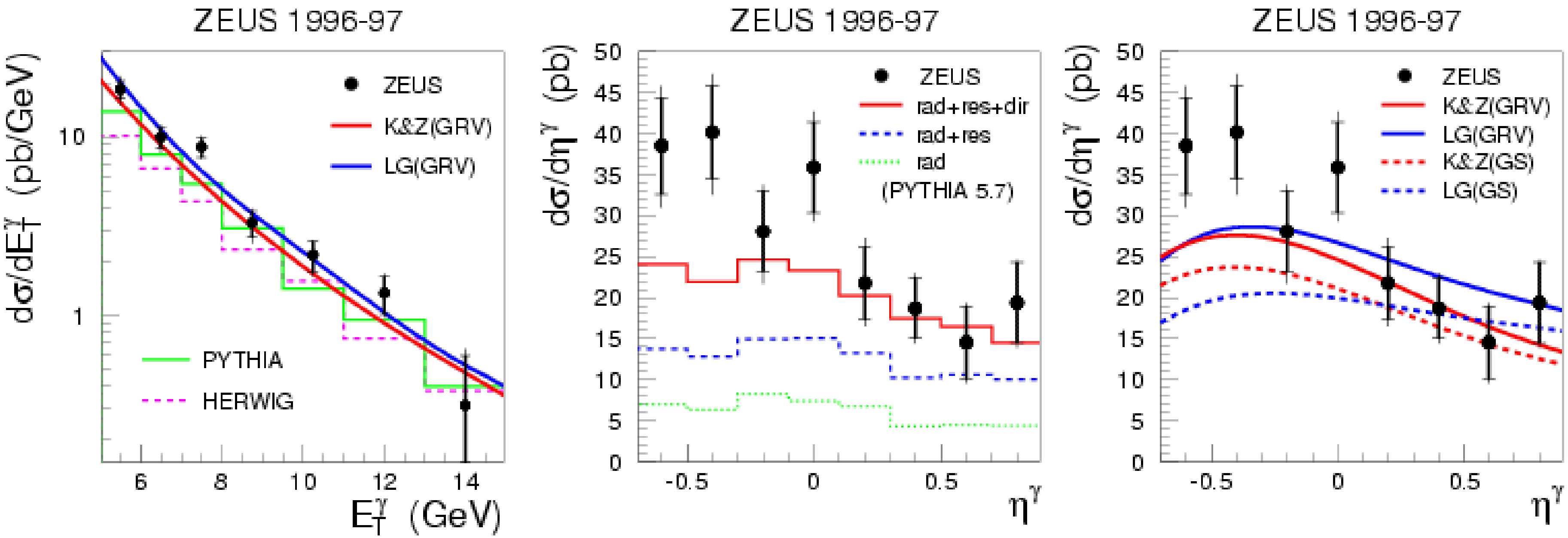
1. Width of photon candidate in Z
2. Fraction of total photon energy in most energetic calorimeter cell

1. Mean transverse shower radius
2. Shower hot core fraction

ZEUS Inclusive Photon Cross Sections

ZEUS, PLB 472 (2000) 175

Photoproduction

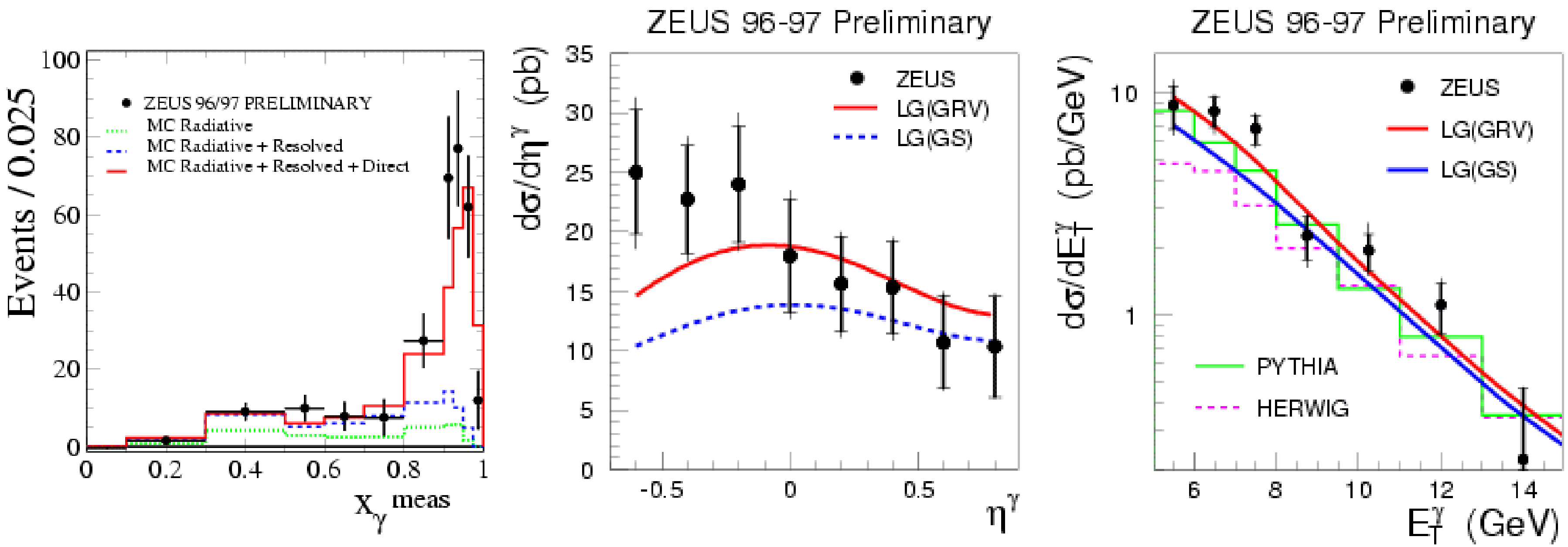


- $d\sigma/dE_T^\gamma$: **all theoretical models describe the shape of the data well**
  PYTHIA does fairly well, HERWIG is a little low in magnitude
- $d\sigma/d\eta^\gamma$: **generally described by LO and NLO over forward rapidities,**
  but there is a possible discrepancy in the rear region
- **Given the discrepancies also seen in HERA dijet, there would appear a need to review the present theoretical modelling of the photon parton structure**

ZEUS Photon + Jet Cross Sections

ZEUS, PLB 472 (2000) 175

Photoproduction

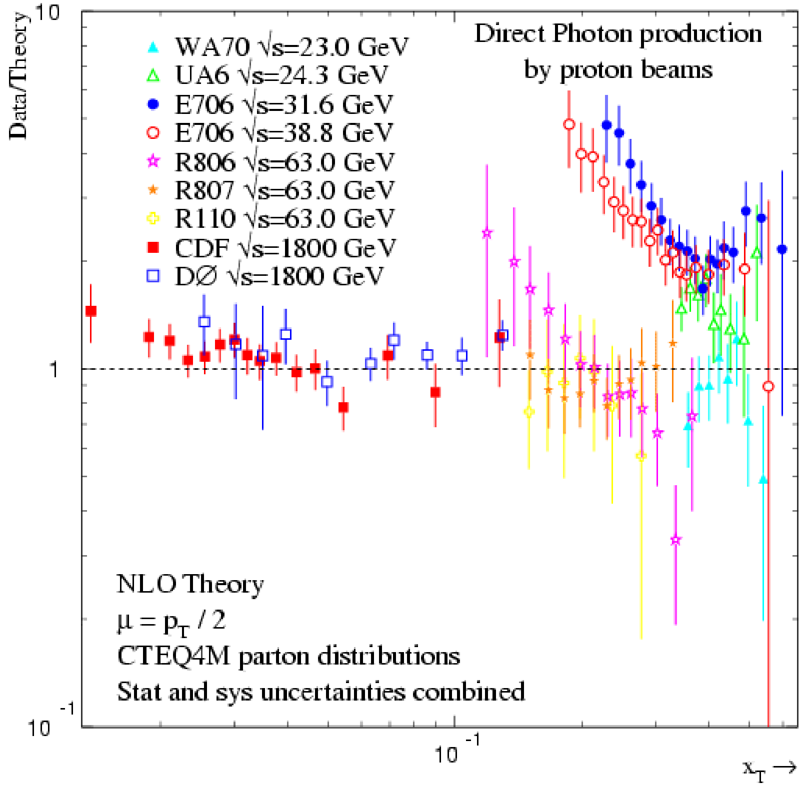


- x_γ = fraction of incoming photon energy taking part in the hard interaction
- Clear peak near 1.0 : corresponding to Direct Compton process
- There is a resolved contribution in x, observation are consistent with MC
- Both the measured and theoretical distributions were found to be of a similar shape to those of inclusive photon production, but less strong discrepancy

HERA kT - Experimental Motivation

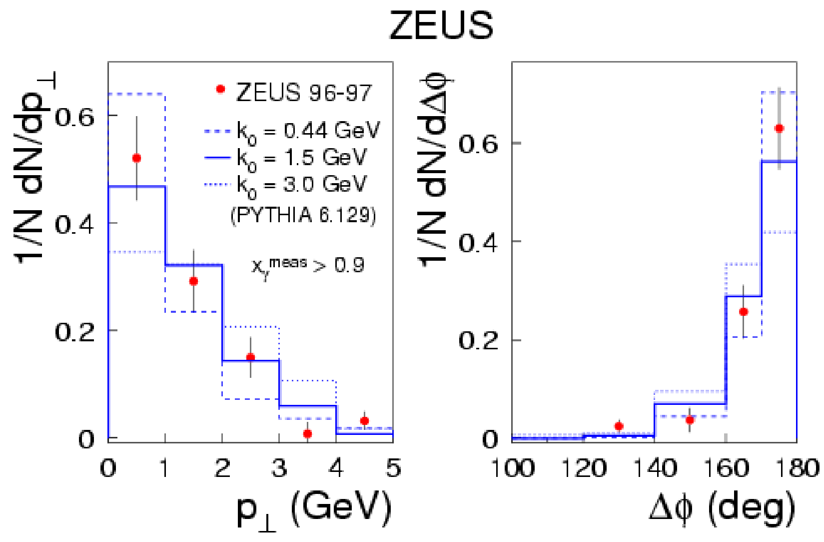
- TeVatron exp. Highlighted serious limitations of current pQCD description of high pT prompt photon production;
  → CDF/D0, E706 and other fixed target exp.
- One offered explanation is that the partons in the proton may have a considerably higher kT (due to soft gluon rad. at low pT)
- kT increase as approximately log with √s
  → 1 GeV for fixed target
  → 2.5 GeV at √s = 630 GeV
  →3~4 GeV for TeVatron at √s = 1.8
- Gaussian smearing of kT gives good aggrement with TeVatron photon data
- Can we see same intrinsic parton kT effect from HERA prompt photon data?
  → Well, the answer is …

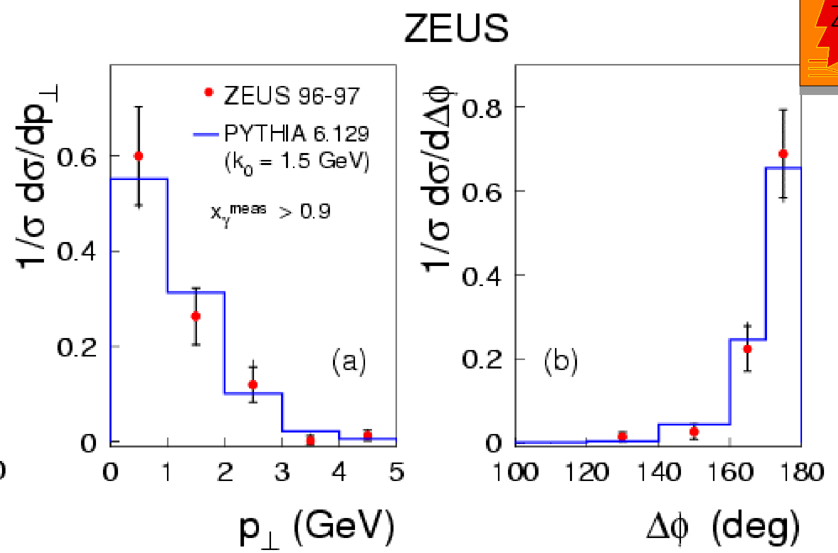
❑ Comparison of photon XT for different photon experiments



❑ Differing various exp have reported excesses at lower xT values compared to NLO predictions

ZEUS Determination of Parton <kT>





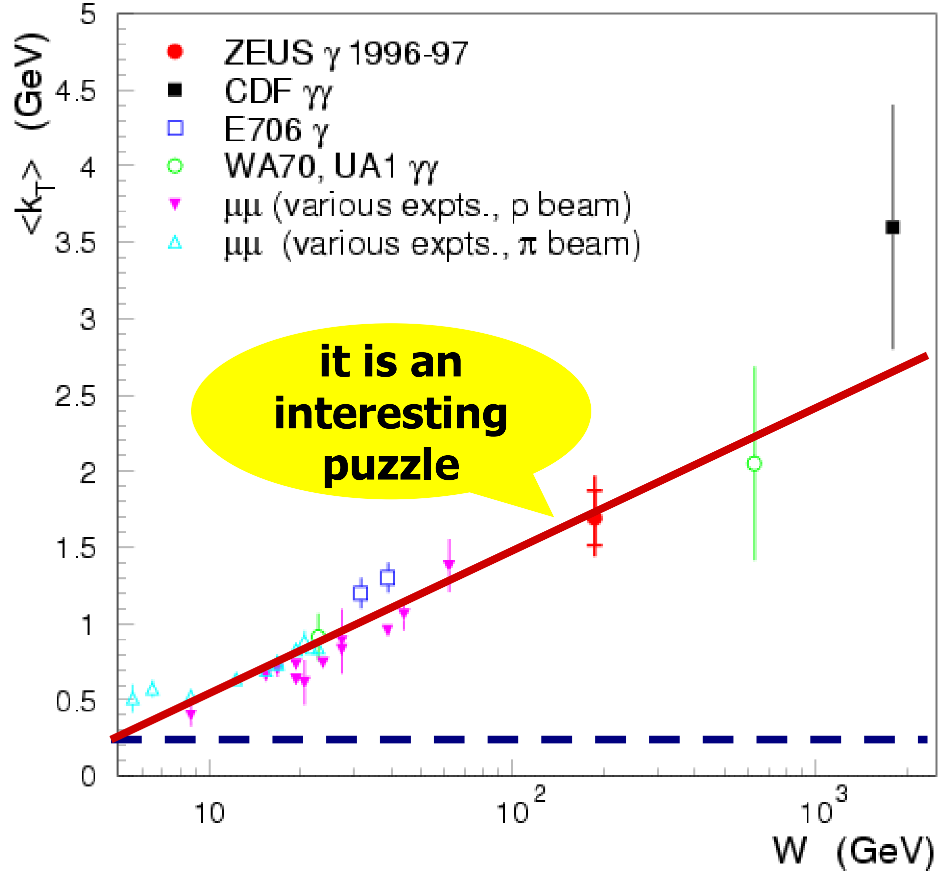
Photoproduction

Procedure to evaluate <kT>

- Select a highly direct-enhanced sample to minimize effects of photon structure
- Modeling kT: Vary 'intrinsic' contribution, k0, in PYTHIA parton shower model
- Fit pT distribution using series of k0 values
- Determine <kT>intr from a fit at the detector level with extra k0 points
- Use PYTHIA again at parton level to incorporate parton shower effects

$\langle k_T \rangle = 1.69 \pm 0.18\ (+0.18, -0.20)\ (\text{GeV})$

A Consistent Picture of kT



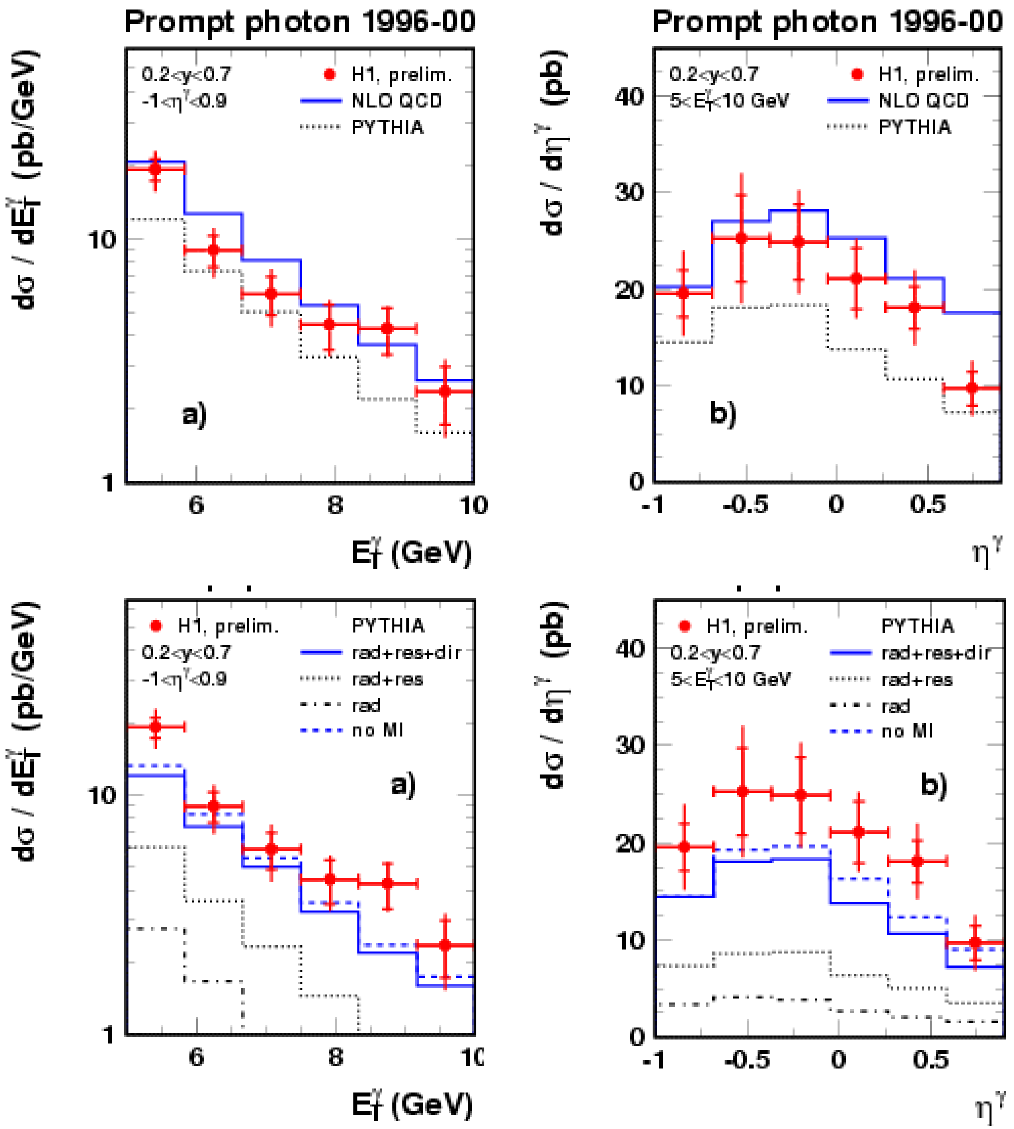
- Many experiments have made measurement of the effective parton kT in the proton
- Lower energies: expect a value ~ 0.5 GeV corresponding to size of the proton
- Higher energies: higher values obtained – initial state parton showers?
- Different exp. use different methods, but the trend is evident
- ZEUS result consistent with this trend

W = invariant mass of photon + jet final state

- There may be an interesting connection between the Tevatron and HERA
- The new CDF/DØ Run2 measurement could add additional info to help interpret the kT effects and test theoretical models…

H1 Inclusive Photon Cross Sections

Photoproduction

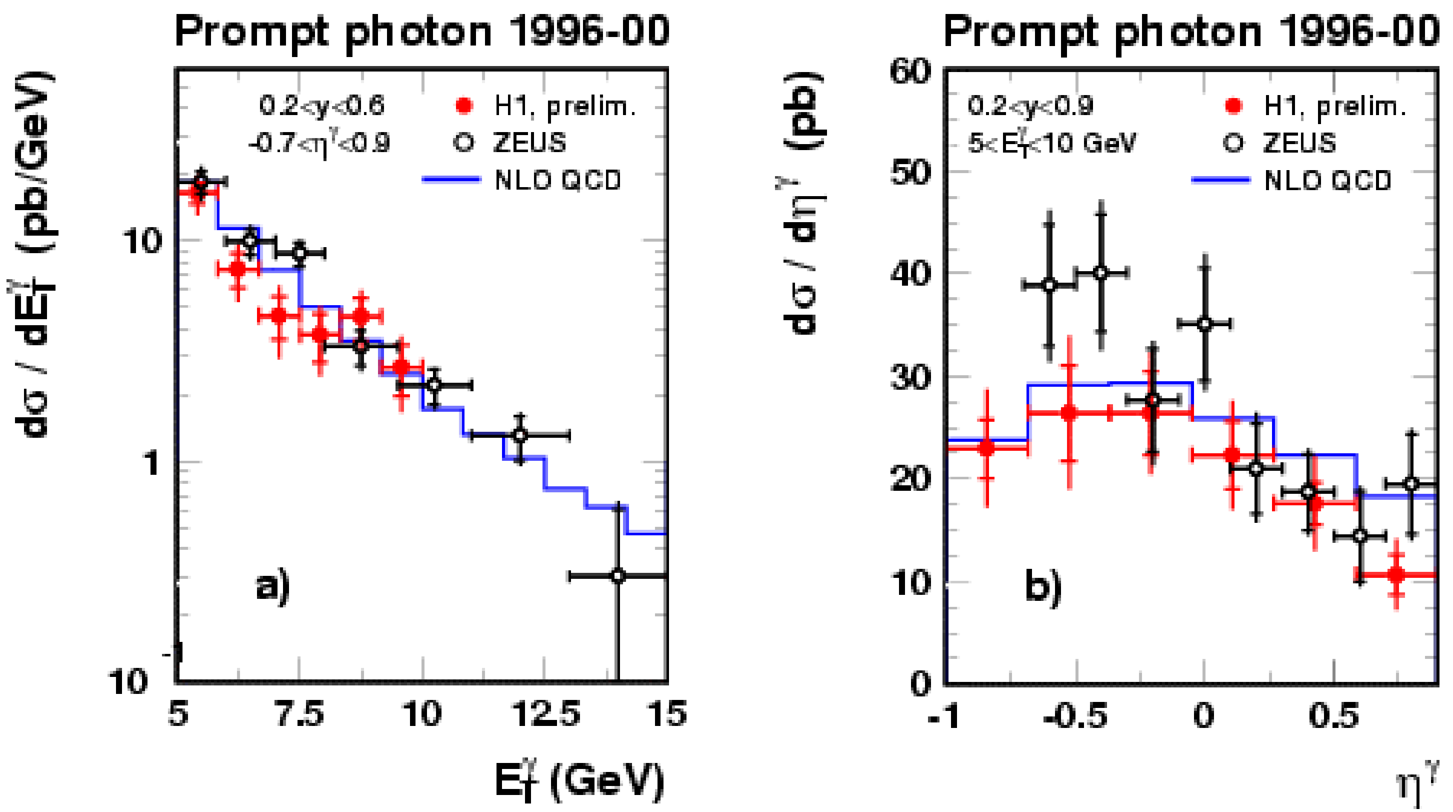


- NLO describes the H1 data quite well, but is above the data in the forward region.
- PYTHIA, shape is OK, but low in normalization(30%)
- PYTHIA indicates effect of MI at large rapidity; would reduce NLO prediction

- NLO pQCD calculation
  Fontannaz , Guillet, Heinrich
  AFG/MRST2
- PYTHIA
  GRV(LO), MI, ISR/FSR

ZEUS Photon vs. H1 Photons

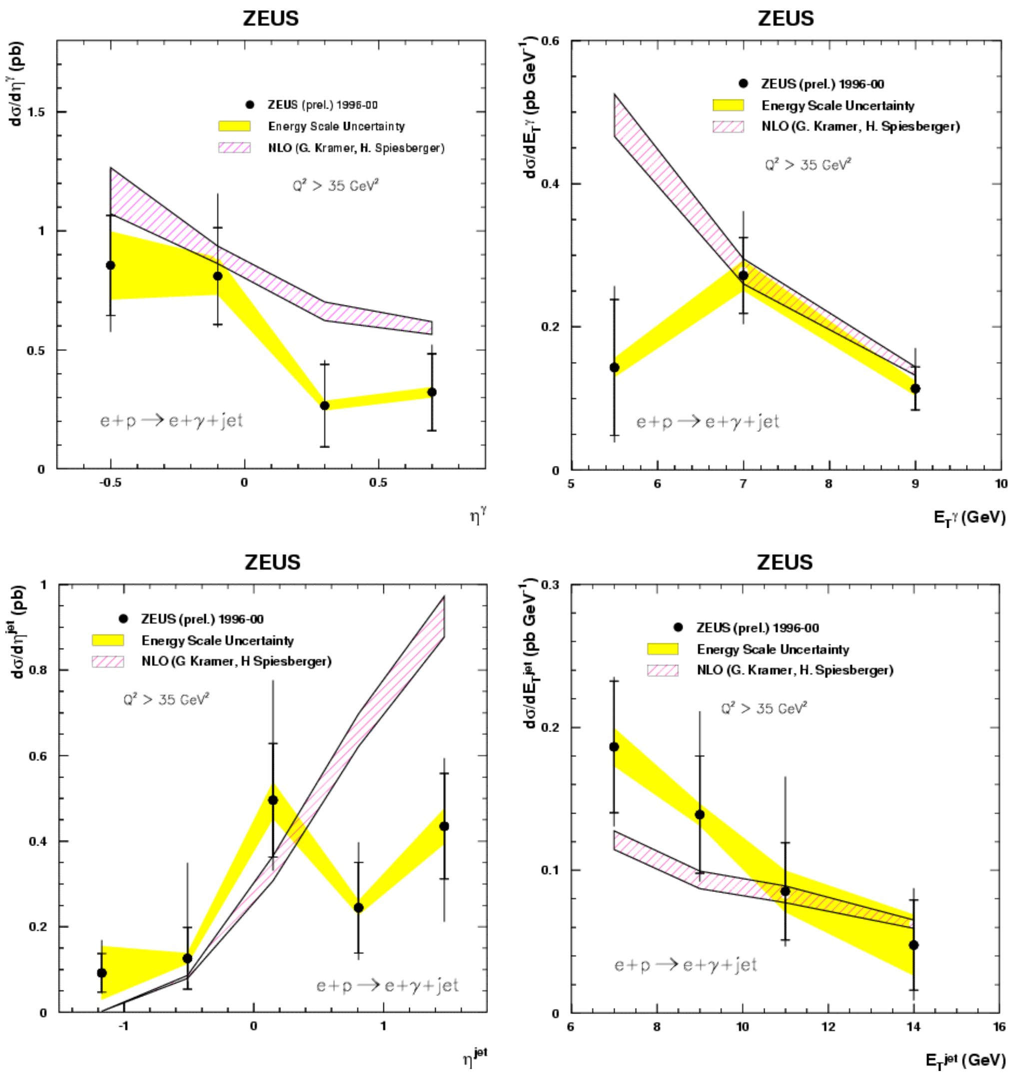
Photoproduction



The H1 data are compared to the results of the ZEUS at *$\sqrt{s}$ = 300 GeV*
The data are consistent, but the H1 data are somewhat lower at small rapidity, where the ZEUS results appear to exceed the NLO.

Prompt Photon Production in DIS at ZEUS

Photon + Jet

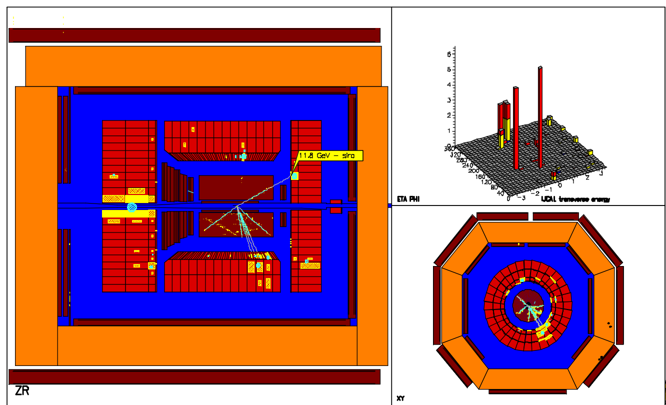


First Observation of prompt photon in DIS at HERA

Total measured x-sections

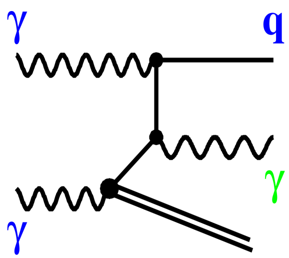
- **Inclusive photon**
  5.95 ± 0.61 (+0.19,–0.26) pb
- **Photon + Jet**
  0.90 ± 0.15 (+0.19,–0.08) pb

Reasonable agreement between the ZEUS data and NLO QCD calculations (by Kramer and Spiesberger)

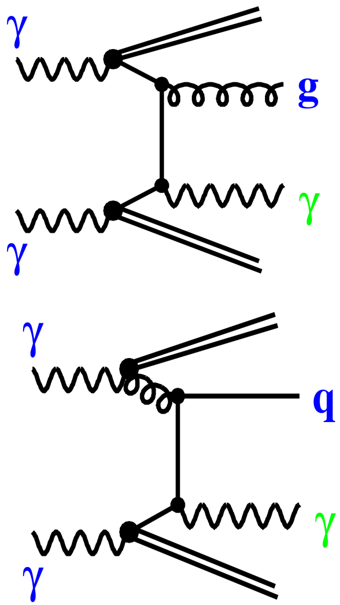


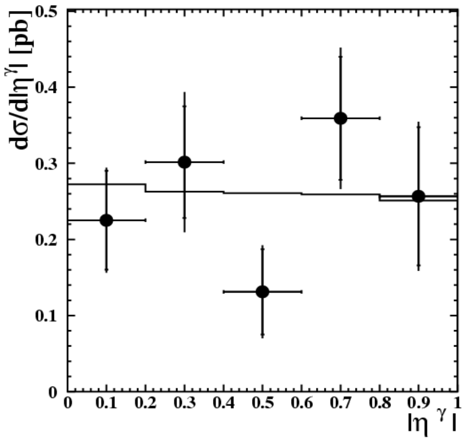
Prompt Photon Production at LEP

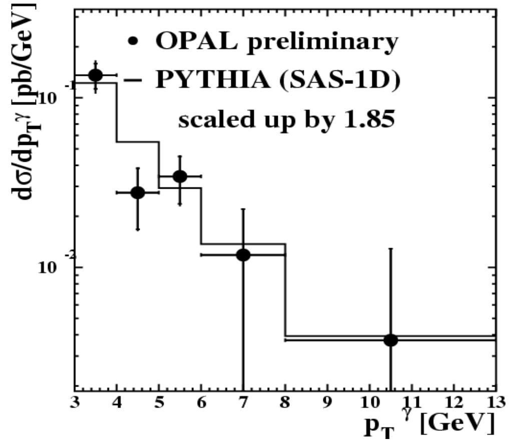
Single-resolved

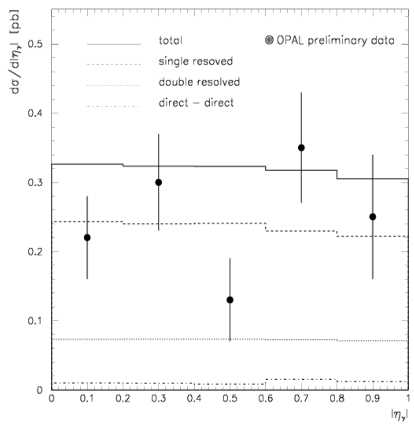


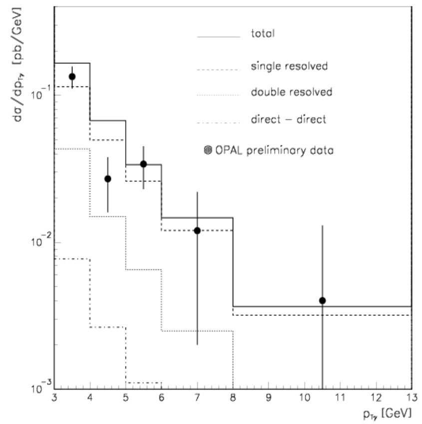
Double-resolved











PYTHIA badly normalized, why? ; good agreement of differential cross-sections with NLO QCD calculations.

Summary and Outlook

- Prompt photon production in Hadronic collisions provides many unique tests of pQCD; generally agreement between QCD model and data.

- Recent Run 1 measurements of inclusive photon production at the Tevatron experiments indicate discrepancies with NLO QCD. kT smearing effects in a simple Gaussian model works fine, though for gluon distribution studies one needs more fundamental approaches. Improved theoretical predictions are being developed. (Theory is being pushed to higher order)

- From ZEUS prompt photon results, there are indications that our current understanding of the photon structure is lacking; It is time to review the current parametrization of the photon parton densities.

- Prompt photon analyses at the Tevatron/HERA are well underway and high luminosity photon data should provide experimental guidance to a better theoretical modeling of prompt photon production.

- It is important to understand QCD photon production in order to reliably search for new physics with photons in the final states.